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WATER PURIFICATION UNIT DEVELOPMENT FOR FIELD ARMY MEDICAL FACILITIES

TECHNICAL REPORT

by

M.K. Lee, P.Y. Yang,
and R.A. Wynveen

April, 1978

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A pilot plant of an integrated water processing system has been developed. The Water Processing System treats nonsanitary wastewaters of the U.S. Army field hospitals either for nonpotable reuse or for surface discharge to the environment and purifies natural fresh and brackish waters for potable use. The Water Processing System consists of four units: (1) a Water Treatment Unit, (2) a Water Purification Unit, (3) a UV/Ozone Oxidation Unit and (4) an		

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Automatic Instrumentation Unit. This report describes the design, configuration and operation of the Water Purification Unit. The primary objective of the Water Purification Unit is to remove most of dissolved contaminants from process water streams. 

The Water Purification Unit consists of three unit processes: (1) depth filtration/ion exchange, (2) reverse osmosis and (3) hypochlorination. The overall contaminant removal efficiencies projected are 98% for total solids and salts and 76% for total organic carbon and chemical oxygen demand. The Water Purification Unit was sized to treat 3,900 gal of hospital wastewaters or natural fresh and brackish water per 20-hour day at a product water recovery of 90%. The overall dimensions of the transportable Water Purification Unit are 9.75 x 5 x 6.75 ft.

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ER-314-7-3

WATER PURIFICATION UNIT DEVELOPMENT
FOR FIELD ARMY MEDICAL FACILITIES

FINAL REPORT

by

M. K. Lee, P. Y. Yang
and R. A. Wynveen

April, 1978

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Prepared Under Contract DAMD17-76-C-6063

by

LIFE SYSTEMS, INC.
Cleveland, OH 44122

for

U. S. Army Medical Research and Development Command
Ft. Detrick, Frederick, MD 21701

EXECUTIVE SUMMARY

American soldiers do not question the quality of the water that comes from the tap. They drink and shower daily without any suspicion. Limited sources of natural fresh water, together with the possibility of ground water poisoning by the enemy, make the reclamation of wastewater for reuse extremely vital to the operation of the combat unit and the Army field hospital in water deficient areas. In response to this need the U.S. Army Medical Research and Development Command has been developing a wastewater reuse system for the field hospital. The system is called a Water Processing System. The interim objective is reuse of nonsanitary wastewater for nonpotable hospital requirements. The ultimate objective is reuse for potable and nonpotable requirements. A full-scale pilot plant of the Water Processing System was designed, built and delivered to the Army under Contract DAMD17-76-C-6063.

The Water Processing System has a nominal product water capacity of 3,500 gal per 20-hour day. The Water Processing System consists of four units: (1) a Water Treatment Unit, (2) a Water Purification Unit, (3) an Ultraviolet/Ozone Oxidation Unit and (4) an Automatic Instrumentation Unit. The objective of this report is to describe in detail the design, configuration and operation of the Water Purification Unit.

There are two types of composite wastes in the nonsanitary wastewater produced from the field hospital. One is a hospital composite waste consisting of shower (51%), operating room (26%), kitchen (12%), laboratory (8%) and X-ray waste (3%). The other is a laundry composite consisting of 67% Type I (color-fast) and 33% Type II (woolens). In addition to the above wastes, the Water Processing System is to treat natural fresh or brackish water for potable use. The projected variations of the contaminant concentrations in the hospital wastewater are 50-1,000 mg/l for total organic carbon and suspended solids, 300-6,000 mg/l for chemical oxygen demand, 500-4,200 mg/l for total solids and 5-900 JTU for turbidity.

There are two modes of operation in the Water Processing System: Reuse Mode and Potable/Discharge Mode. In the Reuse Mode the Water Processing System treats and purifies nonsanitary hospital wastewater for nonpotable reuse. In the Potable/Discharge Mode it simultaneously treats those wastewaters for discharge to the environment while treating natural waters for potable use. The overall product recovery is at least 85% of inflow in the Reuse Mode and 90-95% in the Potable/Discharge Mode. The overall contaminant removal efficiencies are 98.9% for total organic carbon, 99.5% for chemical oxygen demand and 98.5% for total solids.

The primary objective of the Water Purification Unit is to remove most dissolved contaminants from process water streams. In the Reuse Mode, the Water Processing System is the secondary treatment unit for the hospital wastewaters pretreated in the Water Treatment Unit, but in the Potable/Discharge Mode it operates as an independent unit to purify the natural waters for potable use. The overall contaminant removal efficiencies of the Water Processing System are approximately 98% for total solids and salts and 76% for total organic carbon and chemical oxygen demand.

The Water Processing System consists of three treatment processes: (1) natural water pretreatment by the use of depth filtration, carbon adsorption and ion exchange, (2) reverse osmosis and (3) hypochlorination. The natural water pretreatment process separates suspended solids, organisms and hardness from the natural waters. In the reverse osmosis process, dissolved solids and salts are separated from the process water streams. The hypochlorination process is used to maintain 5 mg/l of free residual chlorine in potable and reuse waters for disinfection. The Water Processing System is to be operated 20 hours per day.

The Water Processing System was designed to treat 3,900 gal of the hospital wastewaters or the natural waters per 20-hour day at a product recovery of 90%. The unique requirements for the Water Processing System design are: (1) limited allowance on dimensions, weight and power consumption for transportation and field application; (2) automatic instrumentation and minimum maintenance for unskilled operators; and (3) pilot plant capabilities and semiautomatic instrumentation for performance evaluation and scientific data development.

The reverse osmosis process is the heart of the Water Processing System. It is a membrane separation process in which a semipermeable membrane separates dissolved organic and inorganic contaminants from permeable water. The major components of the reverse osmosis system are a reverse osmosis membrane assembly, a 60 gal feed tank, a series of fine filters and a high pressure pump. A reverse osmosis membrane assembly of four Du Pont Permasep permeators (B-10) was selected due to its demonstrated performance for the Army hospital wastewaters and brackish waters. Each B-10 permeator has a 5.5 in diameter and is 47 in long. The high pressure pump maintains the operating pressure of the membranes at approximately 815 psia. The natural water pretreatment system consists of a depth filter (1 ft diameter x 4.5 ft high), a carbon adsorption column (1 ft diameter x 4.5 ft high) and an ion exchange column (3 ft diameter x 5 ft high). Approximately 2 ft³ of granular activated carbon and 21 ft³ of cation exchange resin are contained in the carbon and the ion exchange column, respectively. The hypochlorination unit consists of a 50 gal hypochlorite tank, a hypochlorite feed pump and static mixers. The overall dimensions of the transportable Water Processing System are 9.75 x 5 x 6.75 ft. The unit is configured so all components are easily accessible.

Both automatic and semiautomatic instrumentations were incorporated into the Water Processing System design to control and monitor the system performance. Only the semiautomatic instrumentation is described in this report. The semiautomatic instrumentation is highlighted by seven automatic fail-safe shutdown controls, 12 readout monitors, ten warning and alarm lights and 29 controls for pumps and valves.

FOREWORD

This study was conducted for the U. S. Army Medical Research and Development Command, Fort Detrick, Frederick, MD, under Contract DAMD17-76-C-6063. The Program Manager was Dr. R. A. Wynveen. Technical effort was completed by Dr. M. K. Lee, Dr. P. Y. Yang, Dr. J. Y. Yeh, D. C. Walter, K. E. Brown, G. G. See and Dr. W. J. Knebel.

Maj. W. P. Lambert and Mr. W. J. Cooper, Environmental Protection Research Division, U. S. Army Medical Bioengineering Research and Development Laboratory, Fort Detrick, Frederick, MD, were the Technical Monitors of this program. We also wish to acknowledge the technical contributions, assistance and program guidance offered by Lt. Col. L. H. Reuter, Maj. W. P. Lambert, Capt. J. J. McCarthy and Capt. B. W. Peterman.

Results of the pilot plant development program under Contract DAMD17-76-C-6063 have been published in six reports as follows:

<u>Title</u>	<u>Report No.</u>
Pilot Plant Development of an Automated, Transportable Water Processing System for Field Army Medical Facilities	ER-314-7-1
Water Treatment Unit Development for Field Army Medical Facilities	ER-314-7-2
Water Purification Unit Development for Field Army Medical Facilities	ER-314-7-3
Advanced Instrumentation Development for a Water Processing Pilot Plant for Field Army Medical Facilities	ER-314-7-4
UV/Ozone Oxidation Technology Development for Water Treatment for Field Army Medical Facilities	ER-314-7-5
Data Acquisition, Monitor and Control System Development for Field Army Medical Facilities	ER-314-7-6

The first report, ER-314-7-1, outlines in brief the overall program for the pilot plant development of the Water Processing System. The succeeding reports present further details on the subsystem developments of the Water Processing System pilot plant. The pilot plant consists of four subsystems: (1) a water treatment unit, (2) a water purification unit, (3) a UV/ozone oxidation unit and (4) an automatic instrumentation unit. This report describes development of the Water Purification Unit.

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ACRONYMS

COD	Chemical Oxygen Demand
DF	Depth Filtration
EP	Equalization/Prescreening
HC	Hypochlorination
IE	Ion Exchange
JTU	Jackson Turbidity Unit
MUST	Medical Unit, Self-Contained, Transportable
O ₃ /UV	Ultraviolet-Activated Ozone Oxidation
RO	Reverse Osmosis
TOC	Total Organic Carbon
UF	Ultrafiltration
WPS	Water Processing System
WPU	Water Purification Unit
WTU	Water Treatment Unit

INTRODUCTION

The U. S. Army has a requirement to provide a mission-oriented medical treatment system which is designed and equipped to facilitate rapid establishment and disestablishment. This flexibility permits immediate response by medical support units to any tactical, environmental or geographical change for combat units. The mobile medical treatment system will provide a contamination-free and controlled environment in which medical, surgical and ancillary procedures, and other supporting functions can be performed. The system has been called Medical Unit, Self-Contained, Transportable (MUST).⁽¹⁾

A sufficient, reliable supply of water with good quality plays a significant role in the deployment of a MUST-equipped hospital into water deficient areas. In order that tactical flexibility of the combat unit and the mobile field hospital should not be limited by fixed fresh water sources, the U. S. Army Medical Research and Development Command (USAMRDC) has been developing a wastewater treatment and purification system for the MUST hospitals. The system is called a Water Processing System (WPS). The interim objective is reuse of nonsanitary wastewaters for nonpotable hospital requirements. The ultimate objective is reuse for potable and nonpotable requirements.

The WPS has a nominal product water capacity of 3,500 gal per 20-hour day. A full-scale pilot plant of the WPS was designed and built by Life Systems under contract with the USAMRDC. The objective of the development program was to:

1. Design, fabricate, check out, deliver and start up a fully-functional MUST WPS Pilot Plant.
2. Design, fabricate, test, install, start up and debug a Data Acquisition, Monitoring and Control System.
3. Provide technical support to insure the operability of the WPS Pilot Plant.

The WPS Pilot Plant consists of four units: (1) a Water Treatment Unit (WTU), (2) Water Purification Unit (WPU), (3) a UV/Ozone Oxidation (O₃/UV) Unit and (4) an Automatic Instrumentation Unit.⁽²⁻⁵⁾

This report describes the design, configuration and operation of the WPU and is intended to be supplementary to LSI Report, ER-314-7-1, entitled, "Pilot Plant Development of an Automated, Transportable Water Processing System for Field Army Medical Facilities."⁽²⁾

WATER PROCESSING SYSTEM

Table 1 shows the two modes of operation in the WPS. In the Reuse Mode (Mode 1) the WPS treats and purifies nonsanitary hospital wastewaters for nonpotable reuse. In the Potable/Discharge Mode (Mode 2) it simultaneously treats those

(1) References cited in parentheses are listed at the end of this report.

TABLE 1 OPERATIONAL MODES OF THE MUST
WATER PROCESSING SYSTEM⁽⁶⁾

<u>Operational Mode</u>	<u>Function</u>	<u>Product Recovery</u>
1. Reuse	● Treatment and Recycle of Nonsanitary Hospital Wastewaters	85%
2. Potable/ Discharge	● Treatment of Natural Fresh and Brackish Waters for Potable and Nonpotable Use	90%
	● Treatment and Discharge to the Environment of Nonsanitary Hospital Wastewaters	95%

same wastewaters for discharge to the environment while treating natural fresh or brackish water for potable use. The overall recovery of product water is at least 85% of inflow for Mode 1 and 90-95% for Mode 2.

Figure 1 is a block diagram of the Reuse Mode. Nonsanitary hospital wastewaters (such as operating room, kitchen, X-ray, laboratory, shower and laundry) are fed to the Equalization/Prescreening (EP) process in which gross suspended solids are removed. In addition, the EP process equalizes time-varying hydraulic loading and concentration variations to result in a more uniform feed to the Ultrafiltration (UF) process. In the UF process, the suspended and dissolved solids with a molecular weight greater than 15,000 are separated to minimize the fouling and maintenance of the Reverse Osmosis (RO) membranes. The function of the RO process is to remove most of the dissolved organics with a medium molecular weight of 150 to 15,000. The residual low molecular weight organic solutes are finally oxidized in the O_3 /UV process to meet the water quality specifications for nonpotable use: 5 mg/l Total Organic Carbon (TOC) and 10 mg/l Chemical Oxygen Demand (COD), or less. The Hypochlorination (HC) process is used to maintain 5 mg/l free-residual chlorine in the product reuse water.

The typical distribution of TOC, COD and total solids concentrations for hospital composite wastewater is also shown in Figure 1. The numbers in parentheses are the typical rejection percents for each unit process. The overall contaminant removal rates projected are 98.9% for TOC, 99.5% for COD and 98.5% for total solids.

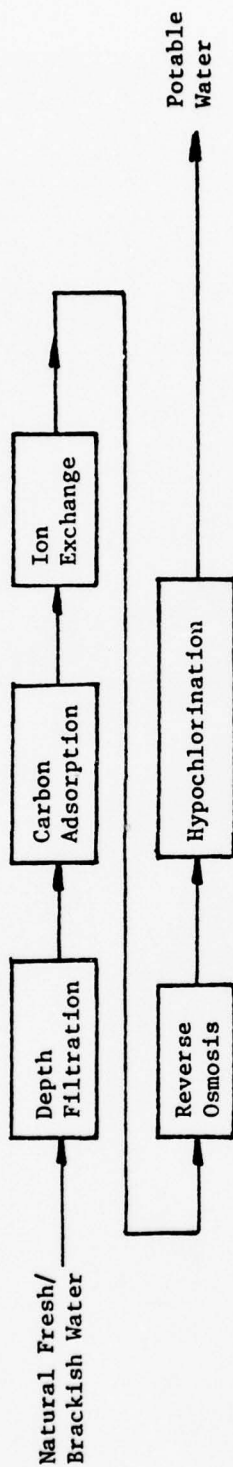
Figure 2 is a block diagram of the Potable/Discharge Mode. The WPS performs two separate, independent functions simultaneously: (1) potable water production from natural fresh or brackish water and (2) hospital wastewater treatment to protect the environment from toxic waste discharge. A total of nine processes are included in both treatment trains. The Ion Exchange (IE) and RO processes are the main stages of the potable water treatment, while the UF process is the heart of the hospital wastewater treatment for discharge. Each train has its own HC unit. The O_3 /UV process in the surface discharge train is used only for certain waste streams with high organic loading, such as kitchen, laboratory, X-ray and composite wastes.

The WPS is a fully automated, integrated water treatment system which fulfills several functional requirements. The flow diagram of the WPS is illustrated in Figure 3. The selection of unit processes and flow paths is determined by pressing proper mode and water source switches on the master control panel. The WPS employs one of the most advanced instrumentation concepts which is highlighted by a minicomputer-based automatic control and monitor and by the capability of the fault detection/isolation and performance trend analysis. For pilot plant testing a number of flexibilities such as semiautomatic instrumentation and manual overrides for major components are incorporated. The WPS can be operated at a remote terminal with all of its control, monitor and data acquisition benefits.

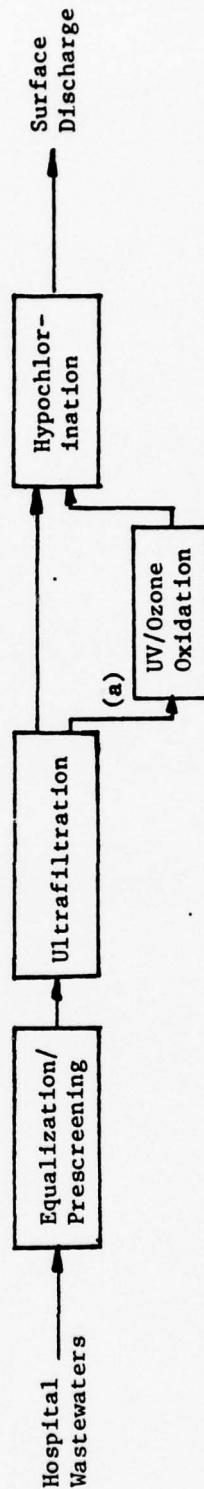
	TOC (mg/l)	COD (mg/l)	Total Solids (mg/l)
Nonsanitary Hospital Wastewaters	50-1,000 ⁽⁷⁾	300-6,000 ⁽⁷⁾	500-4,200 ⁽⁷⁾
↓			
Equalization/ Prescreening (EP)	463	1,875	1,240
↓			
Ultrafiltration (UF)	(73%)	(76%)	(26%)
↓ MW ≤15,000	125	450	918
Reverse Osmosis (RO)	(76%)	(76%)	(98%)
↓ MW ≤150	30 ^(4,8)	108 ^(4,8)	18
↓			
UV-Ozone Oxidation (O ₃ /UV)	(≥84%)	(≥91%)	--
↓	≤5	≤10	--
↓			
Hypochlorination (HC)	--	--	--
↓			
Nonpotable Reuse Water	≤5	≤10	--
<u>Total Removal %</u>	(≥98.9)	(≥99.5)	(≥98.5)

FIGURE 1 UNIT PROCESSES INVOLVED IN REUSE MODE

(1) POTABLE WATER



(2) SURFACE DISCHARGE



(a) For wastes with high organic loading such as kitchen, lab, X-ray and composite.

FIGURE 2 UNIT PROCESSES INVOLVED IN POTABLE/DISCHARGE MODE

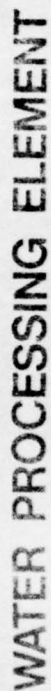


FIGURE 3 FLOW DIAGRAM OF WATER PROCESSING SYSTEM PILOT PLANT

WATER PURIFICATION UNIT

The primary objective of the WPU is to remove most of the dissolved organic and inorganic contaminants from process water streams. In the Reuse Mode the WPU is the principal treatment unit of the WPS for reuse of hospital wastewaters, but in the Potable/Discharge Mode it operates as an independent unit to purify natural waters for potable use.

The projected variations of the contaminant concentrations in feed water streams are 20-850 mg/l for TOC, 100-920 mg/l for COD, 360-3,200 mg/l for total solids and 2,050-3,100 mg/l for salts. The overall contaminant removal efficiencies projected for the hospital composite wastewater and the brackish water are 98% for total solids and salts and 76% for TOC and COD.

Process Description

Figure 4 is a flow schematic of the WPU. Depending on the mode of operation, there are two streams of feed water to the RO feed tank: (1) hospital wastewaters treated in the WTU (Reuse Mode) and (2) brackish or natural fresh water being treated in a depth filter, a carbon column and an ion exchange resin column (Potable Mode). The water collected in the RO feed tank is then pumped through two heat exchangers and a series of 5 and 1 μ filters to the RO membrane assembly. The concentrate stream of the RO membrane assembly is recycled through a backpressure regulator and static mixers to the feed tank. A portion of the concentrate stream is bled to an incinerator in order to control the concentration build-up of contaminants in the system. The permeate stream of the RO membrane assembly is fed either to the O₃/UV Unit in the Reuse Mode or to the HC unit in the Potable Mode. The HC unit consists of a hypochlorite feed tank, a metering feed pump, static mixers and an automatic flow control logic for a proper hypochlorite dose.

Natural water pretreatment consists of three steps: (1) depth filtration, (2) carbon adsorption and (3) ion exchange. The primary function of the depth filter is to remove suspended solids from the brackish or natural fresh water stream. The carbon adsorption column is employed to destroy bacteria and organics (humic acid) which may foul the ion exchange resin. The hardness of the influent water is reduced in the ion exchange column.

The RO process is the heart of the WPU. It is a membrane separation process in which a semipermeable membrane separates dissolved organic and inorganic contaminants from permeable water. The process water is pumped at the rate of approximately 6.6 gpm into the RO membrane assembly which consists of four Du Pont Permasep Permeators placed in a three-stage configuration. The flow rate of RO permeate varies with time, operating conditions and wastewater characteristics. Typical variations of the permeate flow rate range from 3.3 to 4.5 gpm. A small portion of the recycle flow is bled to an incinerator at the rate of 0.33 gpm. The backpressure regulator installed in the concentrate stream of the RO membranes maintains the operating pressure at 815 psia.

The function of the HC unit is to maintain 5 mg/l free-residual chlorine in the potable and the reuse water for disinfection. In order to maintain the required chlorine level, 7% calcium hypochlorite (Ca(OCl)₂) solution stored in

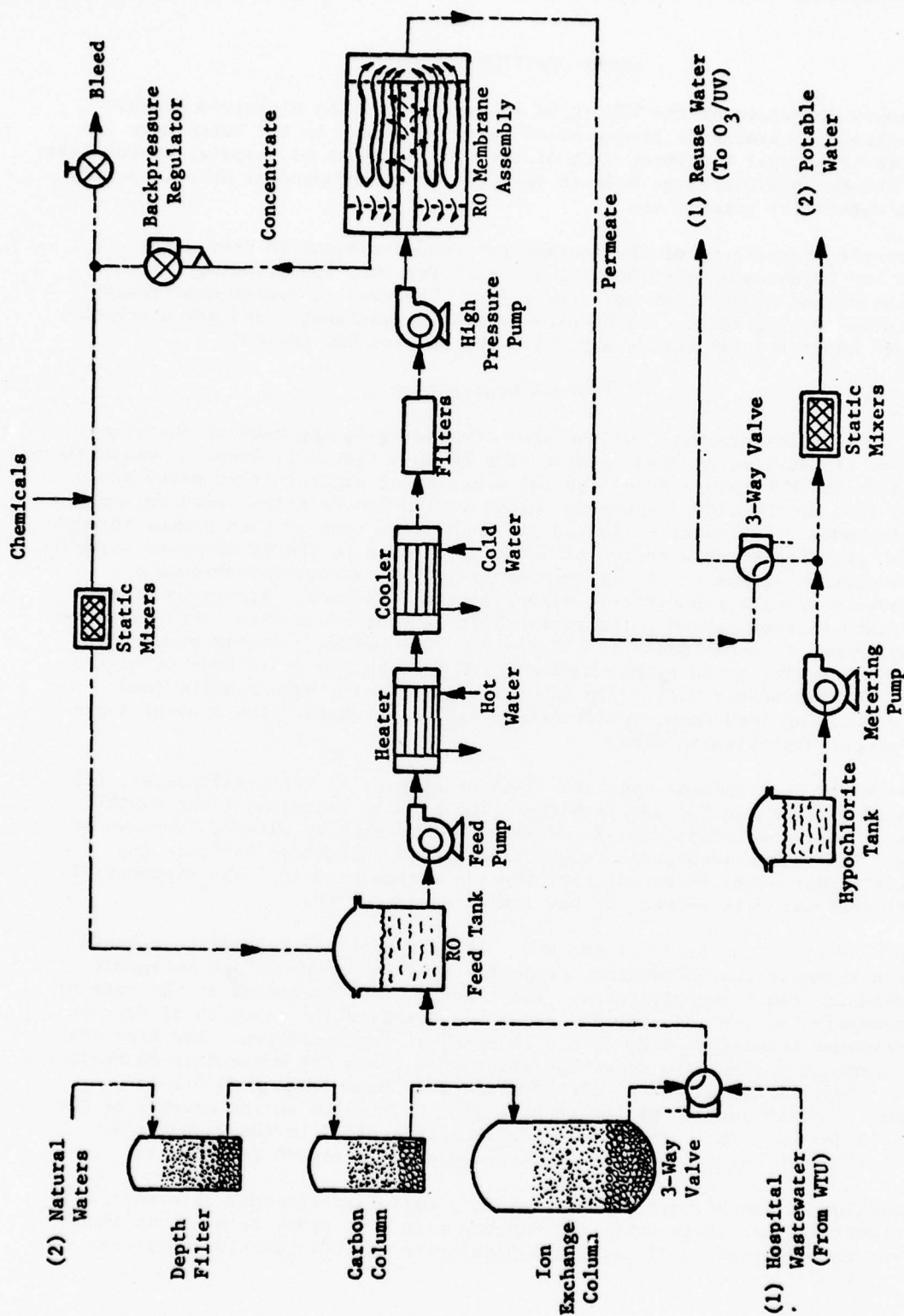


FIGURE 4 FLOW SCHEMATIC OF WATER PURIFICATION UNIT

a 50 gal polyethylene tank is metered by a metering pump and mixed with the RO permeate in static mixers. The flow rate of the hypochlorite is automatically controlled in a feed-forward mode by means of an upstream flow sensor and a pump control logic.

Hardware Description

Figures 5 and 6 are the front and rear views of the WPU. Figure 5 (front view) shows the RO membrane assembly, an IE brine tank, an IE resin column, filters and the semiautomatic instrumentation panels.

The RO membrane assembly consists of four hollow fiber membrane elements installed in a three-stage configuration (2:1:1). The membrane element (Du Pont Permasep Permeator B-10) is 5.5 in diameter x 47 in long. The 3 ft diameter x 5 ft high IE column contains 21 ft³ of resin. The column is fabricated of carbon steel lined with epoxy. The IE brine tank fabricated of PVC has a dry volume of 210 gallons.

The rear view of the WPU (Figure 6) shows chemical tanks, a carbon column, a depth filter and the interface panel. All inputs and outputs of the WPU (mechanical and electrical) go through the interface panel which is shown in Figure 7. Both the carbon column and the depth filter have an overall dimension of 1 ft diameter x 4.5 ft high and are constructed of carbon steel with epoxy lining. The carbon column contains 2 ft³ of granular activated carbon. The depth filter consists of three beds: anthracite (20 in bed height); sand and gravel (6 in). The overall dimensions of the WPU are 9.75 x 5 x 6.75 ft. The unit is configured so all components are easily accessible.

The semiautomatic instrumentation panels shown in Figure 8 are highlighted by seven automatic fail-safe shutdown controls, 12 readout monitors, ten warning and alarm lights, and 29 controls for pumps and valves.

Operation

The WPU can be operated in three modes: (1) Stand Alone, (2) Integrated Semiauto and (3) Integrated Auto. In the Stand Alone mode, the WPU operates as a self-contained unit to purify the natural waters for potable use. In the Integrated modes the WPU operates as a subsystem in the WPS which consists of the WTU, the WPU and the O₃/UV Unit.

In the Stand Alone mode, the only connection needed is system power. With both main and pump power turned on, operation of the unit is initiated by pressing the Reset button on the front panel. Before turning on prime movers, all valve switches should be placed in the proper positions for potable water treatment (Figure 2). The RO feed, high pressure and HC pumps are then turned on sequentially by setting the corresponding toggle switches to the ON positions. As flow develops these switches should be placed in the AUTO positions for the automatic shutdown controls to function. Finally the back-pressure regulator and the HC chlorine dosage control are adjusted to give an operating pressure of 815 psia and a free-chlorine level of 5 mg/l. Operation of the WPU in the Integrated Semiauto mode is basically the same as that in the Stand Alone mode and will not be discussed.

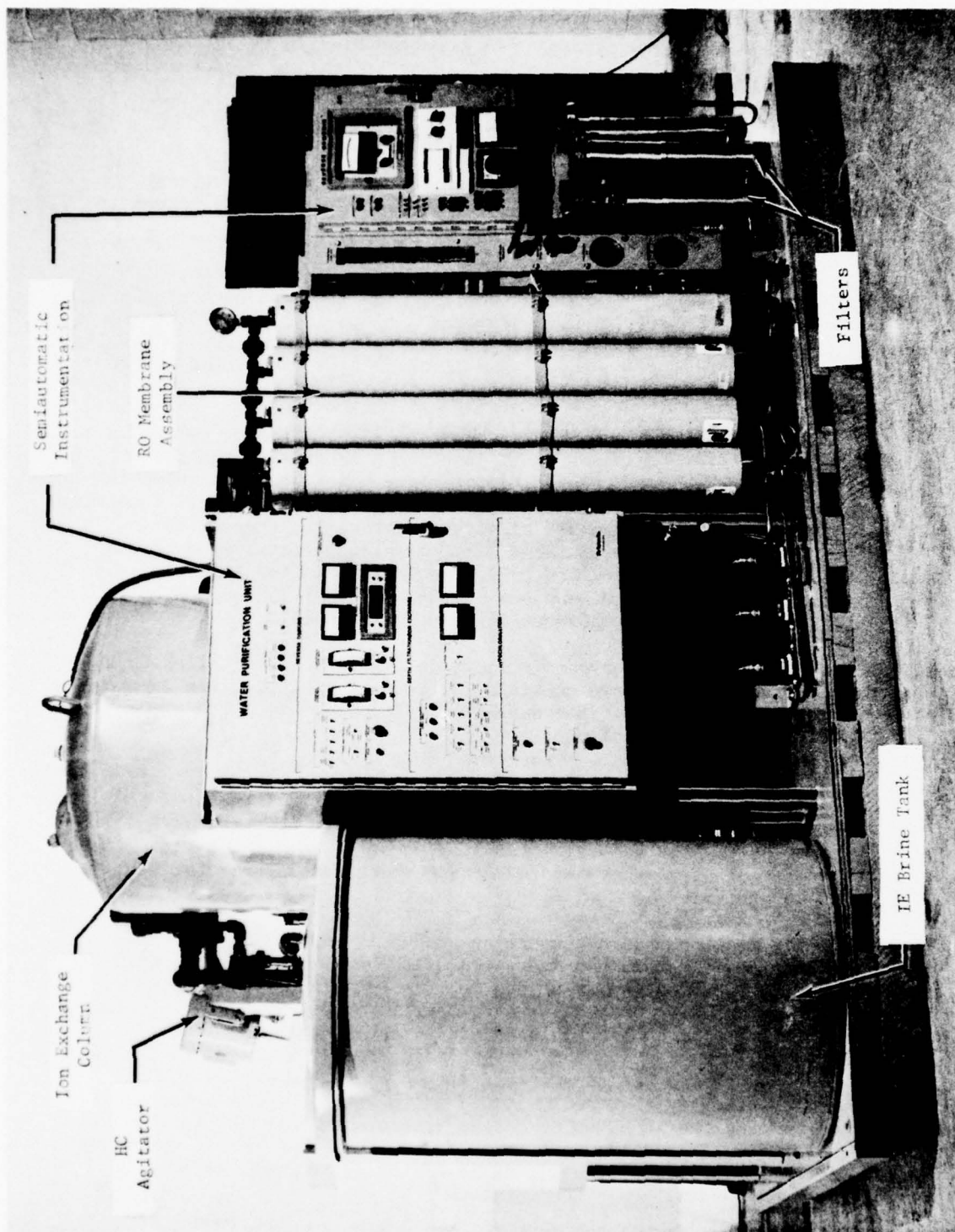


FIGURE 5 WATER PURIFICATION UNIT, FRONT VIEW

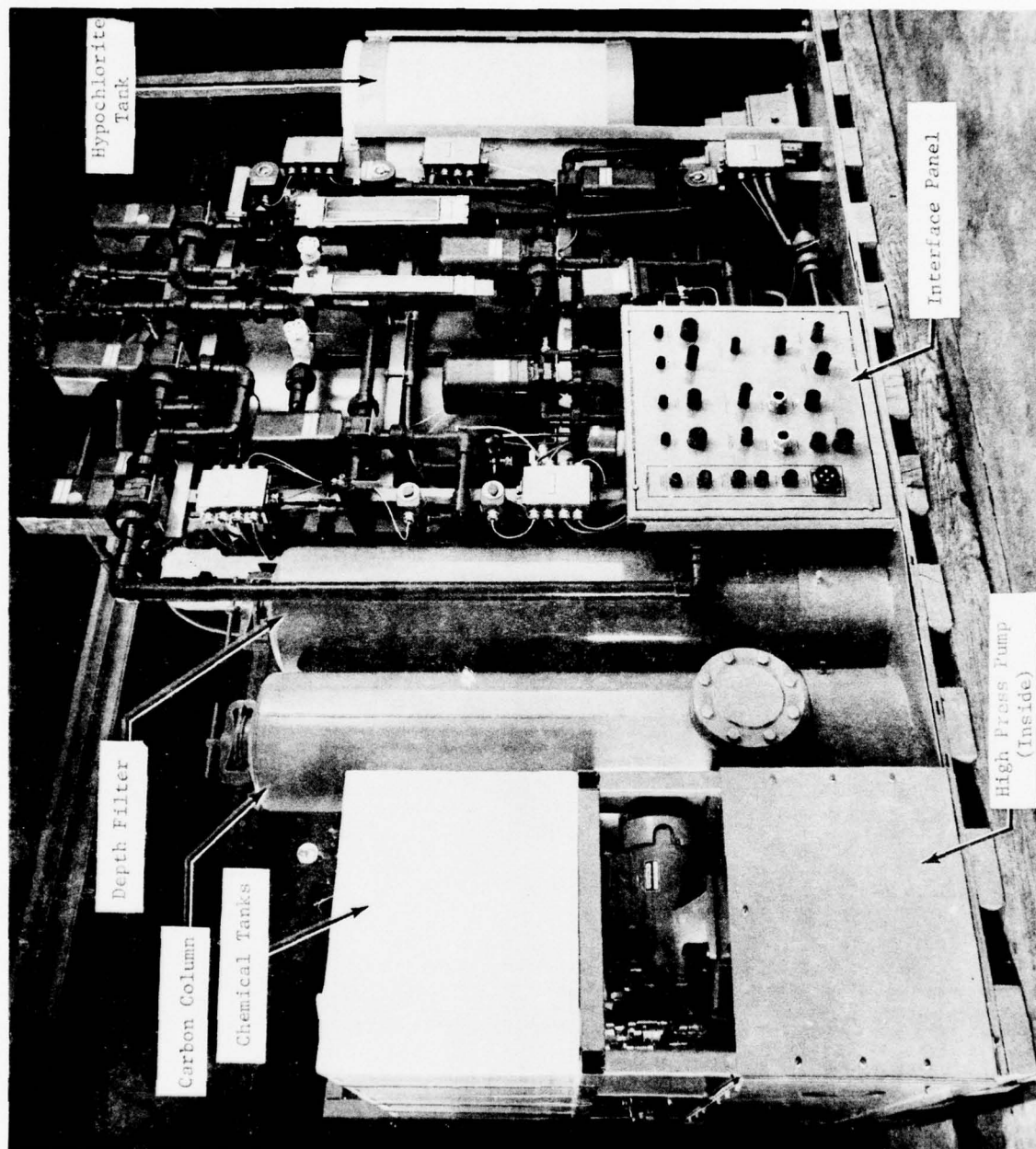


FIGURE 6 WATER PURIFICATION UNIT, REAR VIEW

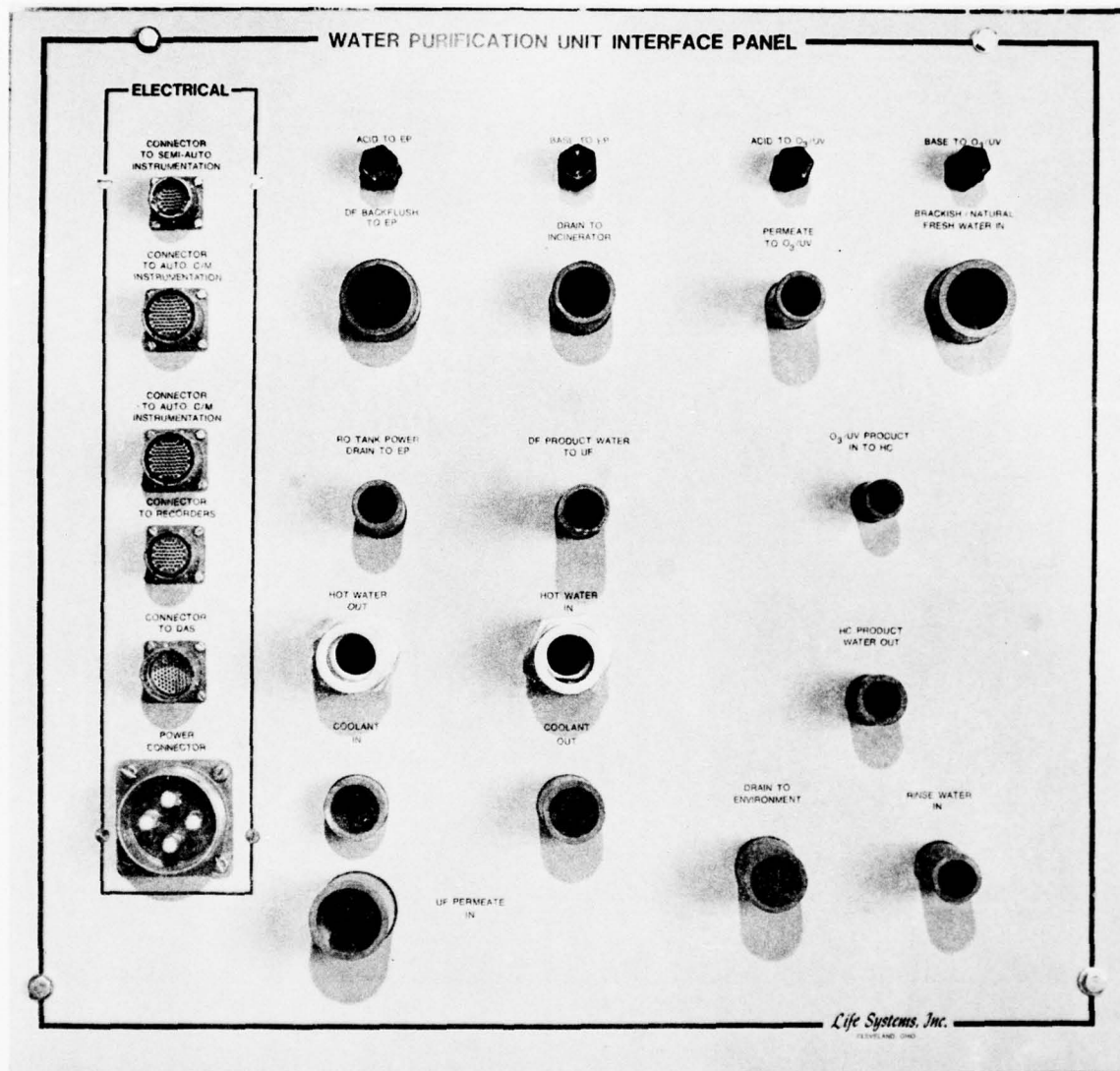


FIGURE 7 INTERFACE PANEL OF WATER PURIFICATION UNIT

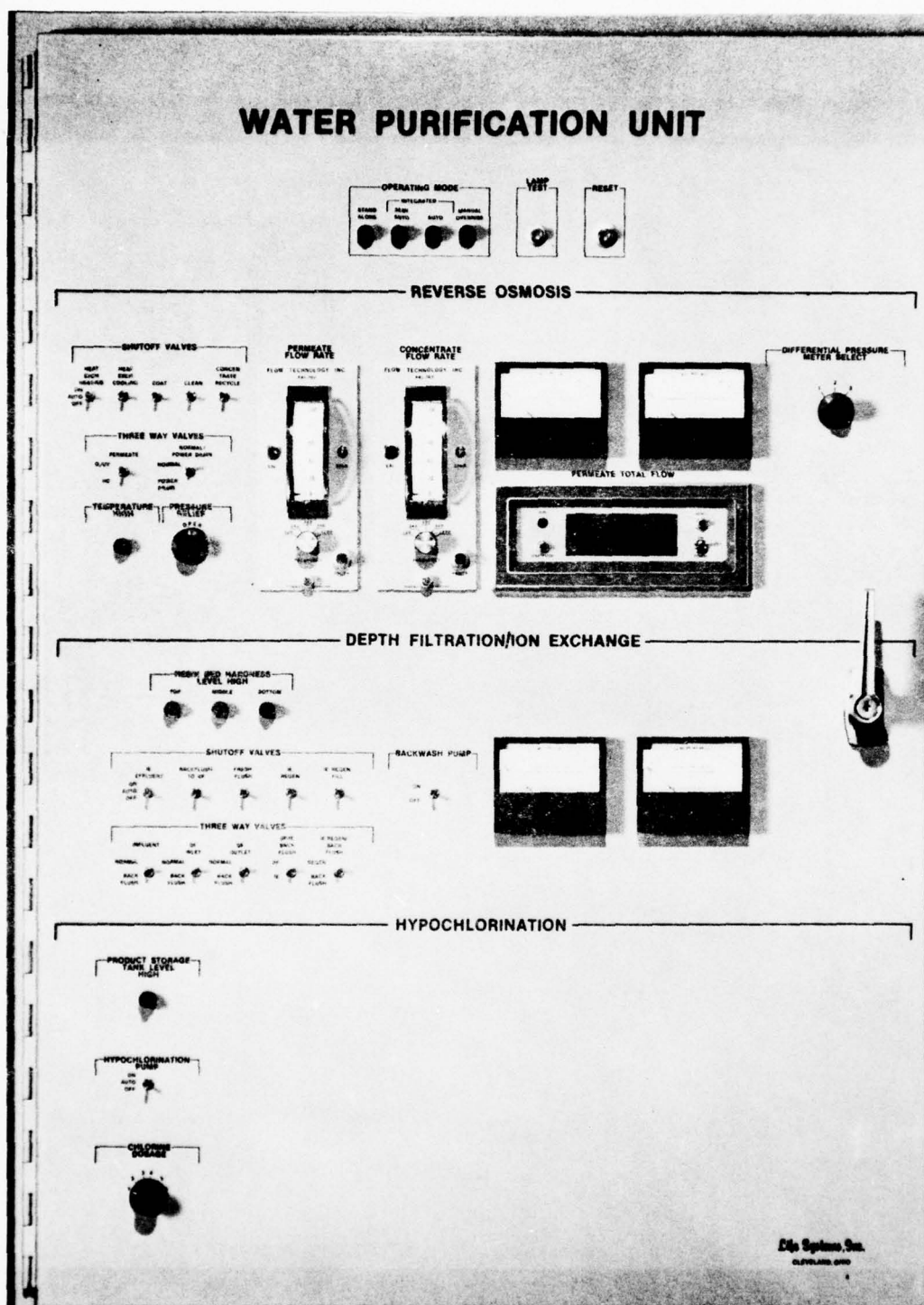
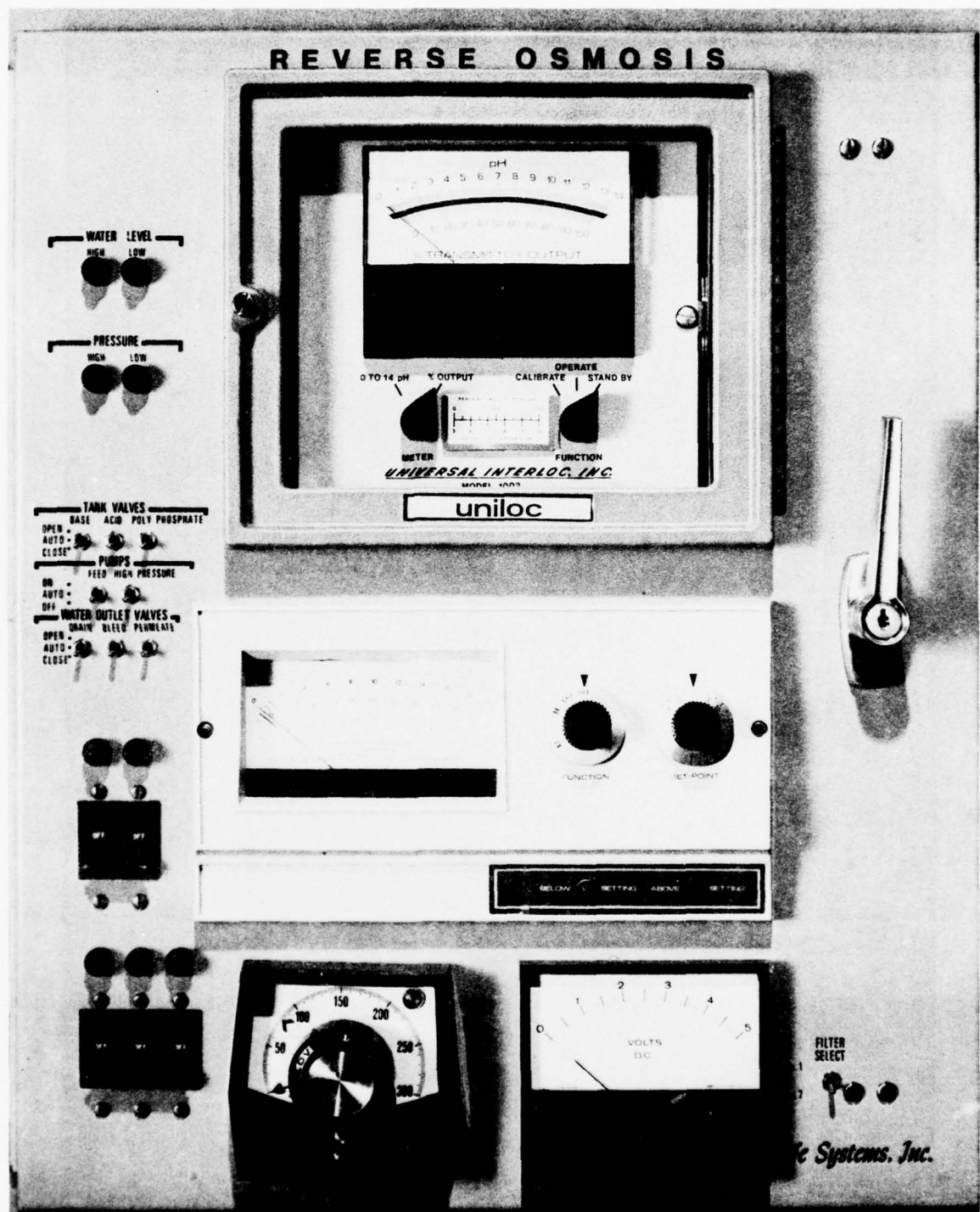


FIGURE 8 SEMIAUTOMATIC INSTRUMENTATION OF WATER PURIFICATION UNIT

--continued

Figure 8 - continued



In the Integrated Auto mode the WPU is connected through two cables to the Automatic Instrumentation Unit and then the WPU is under direct control of the automatic instrumentation. The switches and the shutdown circuits of the WPU are inoperative and the automatic instrumentation controls startup, operation and shutdown of the WPU. The startup and operation of the system is accomplished simply by pressing a single button after Wastewater Source and Product have been selected. Detailed descriptions of the Automatic Instrumentation Unit and the WPS, as well as their operation, can be found elsewhere. (2,9)

The nominal operating conditions of the WPU are summarized in Table 2. The temperature of the natural water influent is projected to vary in a range of 33 to 94 F, depending on geographic locations and time of year. The temperature of shower and kitchen wastes from the WTU is 69 to 125 F. Temperature control to maintain RO operating temperatures at 94 F for shower and kitchen wastes and at 84 F for other wastes is accomplished by two heat exchangers and a temperature sensor installed in the feed line and by a feedback control logic. A residual chlorine level of 5 mg/l in the potable product water is maintained for disinfection. The WPU operates 20 hours per day at a product recovery of 90%.

The WPU is protected from catastrophic damages due to component failures or any abnormal operating conditions. As any alarm conditions defined in Table 3 develop, automatic shutdown controls instantly deactivate both the RO feed pump and the high pressure pump.

The WPU is a highly versatile, transportable pilot plant with a number of benefits incorporated for scientific development and performance evaluation. Table 4 lists some of the highlights and benefits of the WPU instrumentation for each mode of operation.

WATER PURIFICATION UNIT DESIGN

The WPU has been designed to be a self-contained purification unit for the potable water production from natural waters and to be an integratable subsystem in a central WPS for reuse of hospital wastewaters. In addition, the unit is to have a pilot plant capability for scientific data development as well as field and transportable characteristics of low weight, low power, low volume, maintainability and compact design.

Design Specifications

The WPU design specifications are presented in Table 5. The WPU was sized to treat 3,900 gallons of the influent water per 20-hour day at a product recovery of 90%. The 90% recovery does not apply for the natural waters having a total dissolved solids content greater than 3,000 mg/l or a silica content greater than 50 mg/l as SiO_2 . The potable and reuse product waters must have 5 mg/l free-residual chlorine for disinfection. The WPU is to be operated 20 hours per day.

The WPU is capable of processing the hospital wastewater after treatment by the WTU and clarified fresh or brackish water as obtained from natural sources. The projected organic composition of the WTU effluent for the hospital composite

TABLE 2 NOMINAL OPERATING CONDITIONS OF
THE WATER PURIFICATION UNIT

Operating Temperature,	
• Potable Mode (Natural Fresh/Brackish Water)	84
• Reuse Mode	
Shower and Kitchen Wastes	94
Other Wastewaters	84
Operating Pressure,	815
RO Feed Flow Rate, gpm	6.6
Concentrate Recycle Flow Rate, gpm	2.47
Concentrate Bleed Rate, gpm	0.32
Water Level in RO Tank, in	23 to 26
Influent Water	
• Flow Rate, gpm	3.26
• Temperature, F	33 to 125
• pH	6 to 9
Product Water	
• Flow Rate, gpm	2.93
• Temperature, F	83 to 95
• pH	7 to 9
Chlorine Level in Potable and Reuse Water, mg/l	5
Product Recovery, %	90
Operating Time, hr/day	20

TABLE 3 SHUTDOWN DEFINITION AND INDICATION

<u>No.</u>	<u>Parameters</u>	<u>Alarm Condition</u>	<u>Alarm Lamp</u>
1	RO Water Level	≤ 6 in	RO Water Level Low
2	RO Feed Pressure	≤ 1 psig	RO Pressure Low
3	RO Membrane Pressure	≥ 880 psig	RO Pressure High
4	RO Feed Temperature	≥ 97 F	RO Temperature High
5	Hardness of IE Effluent	95% of Bed Used	IE Resin Bed Hardness Level High (Bottom)
6	Product Storage Tank Level	(a)	Product Storage Tank Level High
7	RO Permeate Conductivity	≥ 600 $\mu\text{mho/cm}$ (Potable) ≥ 300 $\mu\text{mho/cm}$ (Reuse)	RO Conductivity High

(a) Not defined yet, since the product water storage tank is not included in the WPE.

TABLE 4 HIGHLIGHTS/BENEFITS OF THE WTU INSTRUMENTATION

Highlights/Benefits	Operating Mode		
	Stand Alone	Integrated Semiauto	Integrated Auto
<u>CONTROLS:</u>			
• Minicomputer-based Automatic Instrumentation			X
• A Single Button Startup			X
• Automatic Shutdown Controls in Case of Emergency	X	X	X
• Automatic pH Control	X	X	X
• Automatic Sludge Removal			X
• Automatic Temperature Control	X	X	X
• Automatic Feed-Forward Control of Hypochlorination	X	X	X
• Remote ON/OFF CONTROL		X	X
• Remote CONTROL			X
• Automatic Cleaning of UF Membranes			X
<u>MONITORS:</u>			
• Written Communication between Operator and the System			X
• Fault Detection/Isolation and Performance Trend Analysis			X
• Remote Monitoring			X
• Digital Readouts	X	X	

TABLE 5 WPU DESIGN SPECIFICATIONS

Maximum Dimensions (L x W x H), ft	11.5 x 9.5 x 6.75
Maximum Dry Weight, lb	6500
Maximum Power, kW	30 for Total WPS
Wastewater Source	Hospital Wastes, Natural Fresh/ Brackish Water
Treatment Capacity, gpd	3900
Product Capacity, gpd	3500
Overall Product Recovery, %	$\geq 90^{(a)}$
Influent Water Quality	See Tables 6 and 7
Effluent Water Quality	See Table 8
Free-Residual Chlorine in Potable and Reuse Water, mg/l	5
Operating Time, hr/day	20
Instrumentation	Semiauto and Auto

(a) 90% recovery does not apply for natural fresh or brackish water having a total dissolved solids content greater than 3000 mg/l or silica content greater than 50 mg/l as SiO_2 .

wastewater is shown in Table 6. Kodak X-Omat developer/fixer, methanol and urea are the major contaminants. The anticipated quality of the brackish surface waters in the United States is presented in Table 7. The values were taken from field analysis data (7) on three surface water samples (Buckeye, Arizona; Denver, Colorado; Rogers Springs, Nevada) and from the data obtained from AAI Corporation (Baltimore, Maryland). The product water either for reuse or for potable use should meet the quality specifications presented in Table 8.

The unique requirements for the WPU design are: (1) limited allowance on dimensions, weight and power consumption for transportation and field application; (2) automatic instrumentation and minimum maintenance for unskilled operators; and (3) pilot plant capabilities and semiautomatic instrumentation for performance evaluation and scientific data development.

Reverse Osmosis System

The RO System is the heart of the WPU. The basic principle and the contaminant removal efficiencies of RO as well as the system design will be described in this section.

Membrane Characteristics

Reverse osmosis is a membrane separation process in which a semipermeable membrane separates most dissolved organics and minerals from a permeable solvent. The separation occurs due to the difference in the mass transfer rates of the solvent and the solutes through the membrane.

Reverse osmosis is the reverse phenomenon of the natural forward osmosis. When two solutions of different concentrations are separated by a semipermeable membrane, the solvent in the dilute solution tends to flow through the membrane to the more concentrated solution, thereby diluting the latter. The solvent flow continues until pressures on both sides of the membrane are in equilibrium (osmotic equilibrium). In reverse osmosis, the direction of the natural osmotic flow is reversed by applying a hydraulic pressure to the more concentrated solution. In order to obtain reasonable flow rates of the solvent, the applied hydraulic pressure should be much greater than the osmotic pressure by the concentration difference. Reverse osmosis systems are operated typically at a pressure differential of 300 to 1500 psid (psi-differential).

Rejection of organics by RO membranes improves with increasing molecular length and size. Organic compounds with molecular weights greater than 150 tend to be rejected by the RO membranes. On the other hand, small compounds containing up to four carbon atoms which have hydrogen-bonding characteristics similar to water are poorly rejected. Ionic species are highly rejected by interaction with fixed charges on the membrane surface. Therefore, typical simple ionic species such as calcium, sodium and sulfate ions are highly rejected. In addition, the RO membranes are known to be capable of removing biological and colloidal matter.

Performance of a RO membrane is usually characterized by its solute rejection (R_m) and by the permeate flux (J_p). The rejection R_m of a solute by a membrane may be defined as:

TABLE 6 ESTIMATED ORGANIC COMPOSITION OF HOSPITAL
COMPOSITE ULTRAFILTRATION PERMEATE⁽¹⁰⁾

<u>Components</u>	<u>Concentration</u>
Methanol	29.8 μ l/l
Acetone	6.3 μ l/l
Acetic acid	3.4 μ l/l
Diethyl ether	0.6 μ l/l
N,N-Diethyl-m-toluamide	0.8 mg/l
Ethanol	0.5 μ l/l
Oleic acid	0.5 μ l/l
Phenol	1.3 mg/l
Urea	18.0 mg/l
Kodak X-Omat Developer	942 μ l/l
Kodak X-Omat Fixer	942 μ l/l

TABLE 7 ANTICIPATED WATER QUALITY FOR
BRACKISH SURFACE WATERS

<u>Contaminants</u>	<u>Concentration, mg/l</u>
<u>General</u>	
Total Dissolved Solids, mg/l	1,800-3,200
Suspended Solids, mg/l	10-100
Turbidity, NTU	5-200
Conductivity, μ mhos/cm	2,000-9,000
pH-Value	6-9
Hardness (as CaCO_3), mg/l	200-2,000
<u>Metals</u>	
Calcium, mg/l	50-500
Copper, mg/l	0-2.0
Iron, mg/l	≤ 1
Magnesium, mg/l	20-200
Sodium, mg/l	300-1,200
Potassium, mg/l	1-30
Manganese, mg/l	0-1.5
<u>Nonmetals</u>	
Bicarbonate or Carbonate, mg/l	100-500
Chloride, mg/l	300-1,500
Nitrate-Nitrogen, mg/l	5-50
Total Phosphate, mg/l	0-20
Sulfate, mg/l	100-1800
Bromide, mg/l	0-10
Fluoride, mg/l	0-10
<u>Miscellaneous</u>	
Silica, mg/l	5-50
Hydrogen Sulfide, mg/l	Trace

TABLE 8 POTABLE AND REUSE WATER SPECIFICATIONS⁽¹¹⁾

<u>Contaminant</u>	<u>Maximum Water Quality Standards mg/l (unless otherwise stated)</u>
Total Organic Carbon	5.0
Chemical Oxygen Demand	10.0
Alkyl Benzene Sulfonate	0.5
Ammonia	0.5
Arsenic	0.05
Barium	1.0
Cadmium	0.01
Chloride	600.0
Chromium (hexavalent)	0.05
Copper	1.0
Cyanide	0.2
Fluoride	4.0
Iron	0.3
Lead	0.05
Magnesium	150.0
Manganese	0.05
Nitrate - Nitrogen	10.0
Phenolic Compounds	0.001
Selenium	0.01
Silver	0.05
Sulfate	400.0
Total Solids	1500.0
Color	50.0 Units

$$R_m = 1 - C_p / C_f \quad (1)$$

where C_p and C_f are the solute concentrations in the permeate stream and the feed water, respectively.

Provided that transport of water through the membrane governs the rate of permeation, the permeate flux of water, J_p , can be related to the driving force, ΔP , by:

$$J_p = K \frac{(\Delta P)^n}{\mu \delta} \quad (2)$$

where μ = viscosity of water,
 δ = membrane thickness,
 K = permeability of the membrane, and
 n = constant.

The driving force, ΔP , is defined by

$$\Delta P = (p_c - p_p) - (\pi_c - \pi_p) \quad (3)$$

where p is the hydraulic pressure, π is the osmotic pressure and the subscripts c and p signify the concentrate and the permeate stream, respectively. In a dilute, ideal solution, the osmotic pressure can be approximated as:

$$\pi \cong cRT \quad (4)$$

where c = solute concentration,
 R = gas constant, and
 T = absolute temperature.

System Design

Modular membrane systems can be designed to operate in one of several process configurations, i.e., semibatch, once-through continuous, recycle-and-bleed continuous, stages in series, stages in parallel, etc. Three common system designs and their descriptions were presented in a previous report.⁽³⁾ Due to the requirements for a high product recovery and the minimum concentrate flow of a membrane selected, a recycle-and-bleed mode of operation was selected in a staged arrangement of membranes. The RO separation system is schematically shown in Figure 9. Detailed design of the RO membrane assembly is presented in the next subsection.

The RO system consists of the RO feed tank, heat exchangers, pumps, filters, the RO membrane assembly and static mixers for pH adjustments. The water in the feed tank is pumped through two heat exchangers and a series of filters to the RO membrane assembly. The concentrate stream of the RO membrane assembly is recycled back to the feed tank to achieve a 90% water recovery. A portion of the concentrate stream is bled to an incinerator in order to control the concentration build-up of contaminants in the system. The permeate flow rate varies with time due to variations of the total solids concentration in the feed water. Since the permeate flow rate should be greater than the required

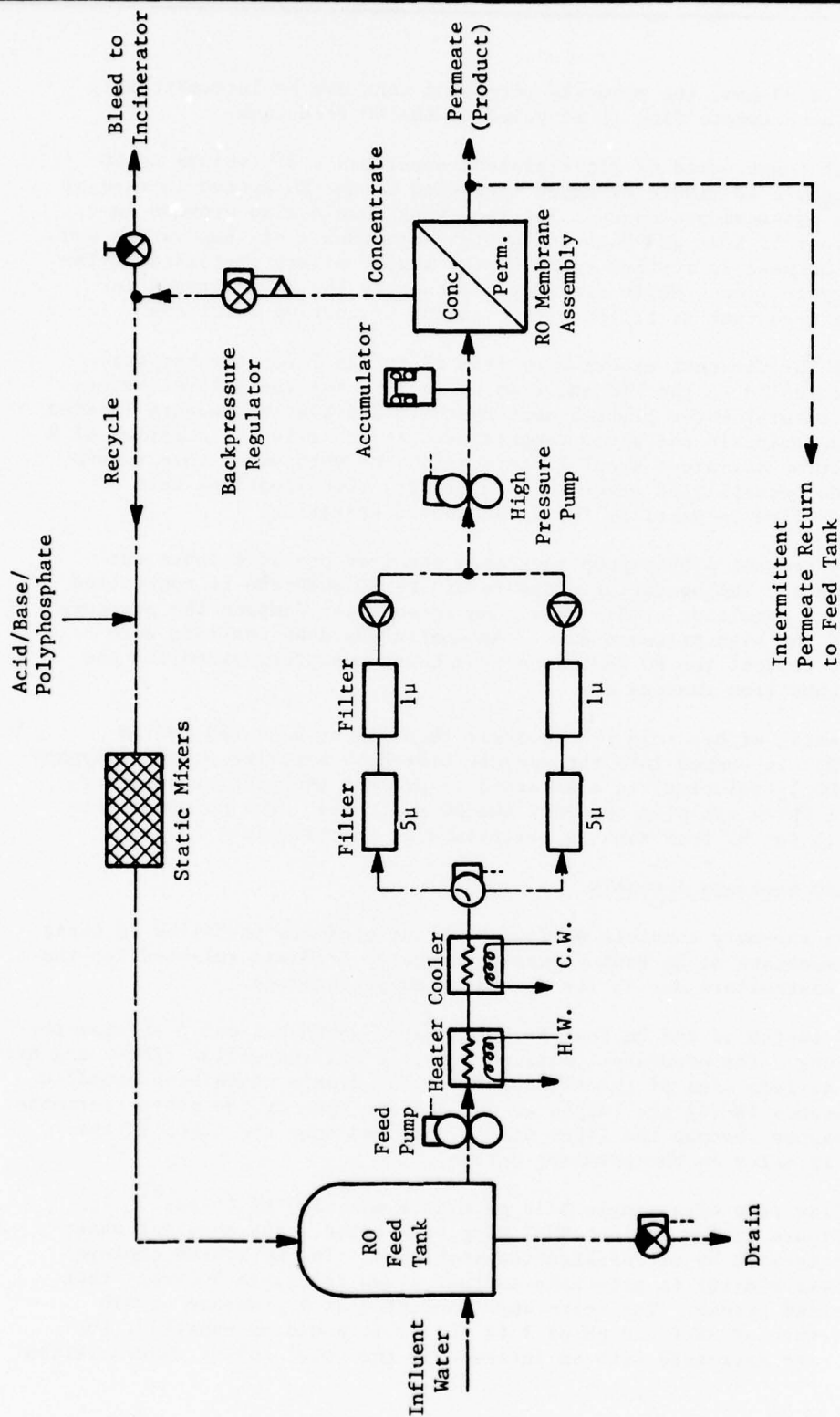


FIGURE 9 REVERSE OSMOSIS SYSTEM SCHEMATIC

minimum rate of 2.93 gpm, the permeate receiving tank may be intermittently full and then the permeate flow is recycled to the RO feed tank.

The RO feed tank constructed of 316 stainless steel has a dry volume of 60 gal which provides a 20-minute extended operation of the RO system in case of failures in the upstream processes. The feed tank should also provide an adequate reservoir of heat and mass for proper adjustments of temperature and pH. The pH adjustment is further aided by the static mixers installed in the concentrate recycle line. While cleaning and coating the RO membranes for maintenance the feed tank is filled with cleaning or coating solutions.

Temperatures of the influent waters vary from 67 to 125 F for the hospital wastewaters pretreated in the WTU and from 44 to 89 F for the natural waters treated in the natural water pretreatment system. Two heat exchangers located in the feed line maintain the water temperatures at 82 to 94 F. A series of 5 micron and 1 micron stainless steel filters with a polypropylene core remove suspended solids precipitated after pH adjustments. Two identical sets of filters are installed in parallel for a continuous operation.

A positive displacement piston pump increases the feed pressure above the operating pressure. The operating pressure of the RO membrane is controlled by a backpressure regulator at 815 psia. An accumulator dampens the pressure fluctuations of the high pressure pump. Automatic shutdown controls were incorporated to protect the RO membranes from being overpressurized and the high pressure pump from running dry.

For pH adjustments, either acid (2N sulfuric (H_2SO_4)) or base (2N sodium hydroxide (NaOH)) is pumped into the recycle line by a metering pump. Polyphosphate (10% ($NaPO_3$)₆ solution) is also added to prevent the precipitation of calcium sulfate which can plug and foul the RO membranes. The polyphosphate concentration in the RO feed tank is maintained at approximately 10 ppm.

Design of the RO Membrane Assembly

The RO membrane assembly consists of four membrane elements installed in three stages. A RO membrane of Du Pont Permasep Permeator B-10 was selected for the MUST hospital wastewaters due to its demonstrated performance.

Figure 10 is a sketch of the Du Pont B-10 Permeator which has a 5.5 in diameter and is 47 in long. The permeator contains nearly a million hollow fibers and has a total fiber surface area of about 1,800 ft². The fibers containing aromatic polyamide membranes (B-10) are looped at one end and open at the other (permeate end). Water passes through the fiber walls, into and down the bores of the fibers, where it exits as the permeate stream.

The permeate flow rate of a single B-10 permeator measured by Gollan⁽⁷⁾ is presented in Figure 11 for various MUST hospital wastes. The hospital wastewaters were pretreated by ultrafiltration membranes. The RO system employed for the tests was similar in principle to that shown in Figure 9 except that there was no bleed stream. The tests were conducted at a pressure of 815 psia, a temperature of 85 F and pH of 7 to 8. As it would be expected, the permeate flow rate decreased with an increase of the total solids concentration.

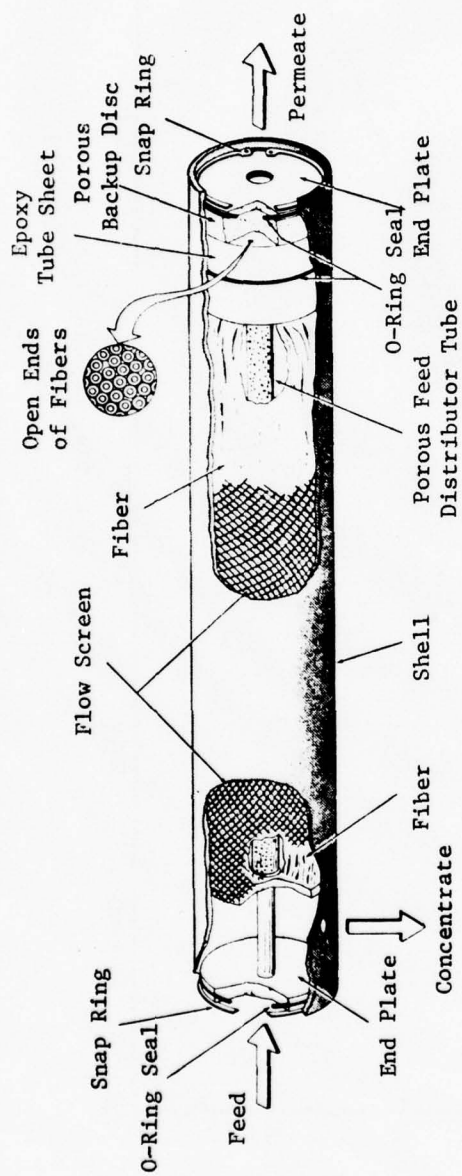


FIGURE 10 CUTAWAY DRAWING OF PERMASEP PERMEATOR

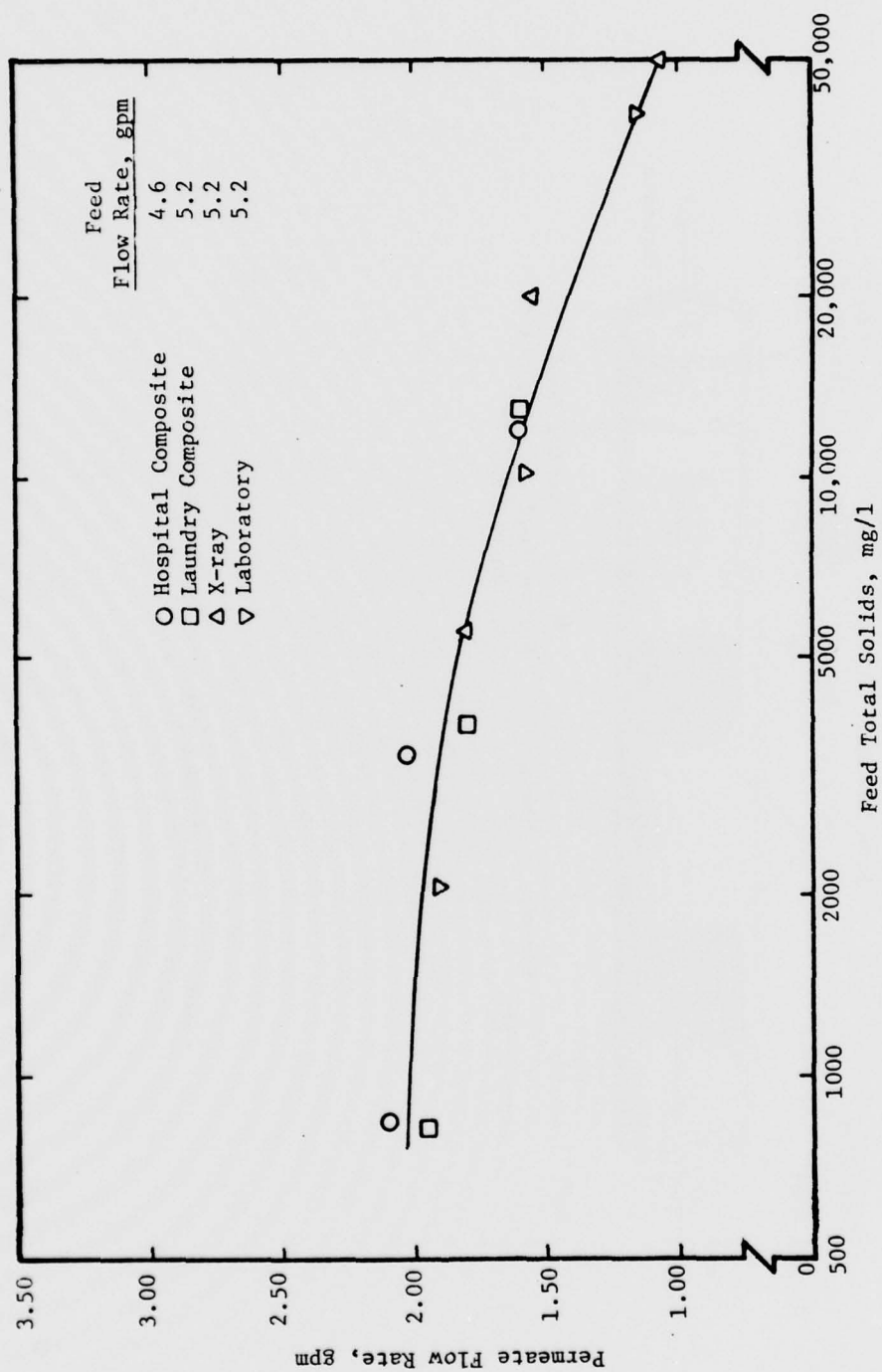


FIGURE 11 EFFECT OF THE FEED TOTAL SOLIDS CONCENTRATION ON THE PERMEATE FLOW RATE OF A B-10 PERMEATOR (7)

It is noted that in the tested range the permeate flow rates for all wastes are greater than 1 gpm.

In addition to the total solids concentration, other contaminants such as TOC and colloidal matter affect the permeate flow rate. As processing continues in a 20-hour operation cycle, the concentrations of various contaminants in the RO system build up. Since the product water recovery reflects the buildup of various contaminants in the system, it may be a more representative design parameter than total solids alone. Table 9 presents the permeate flow rates at product recoveries of 80 and 95%. For the design value of a 90% recovery, permeate flow rates greater than 1.1 gpm can be anticipated.

The permeate flow rates of the B-10 membrane for synthetic surface waters (Table 7) varied from 0.7 to 1.3 gpm, depending on the brackish water processed. No pretreatment was made except for the Colorado surface water which was pretreated by ion exchange to reduce hardness. Provided adequate pretreatments were incorporated into the WPU, an average permeate flow rate of 0.8 gpm for the single B-10 membrane was selected as a minimum flow rate for the design of the WPU. Four B-10 membranes were then needed to meet the required permeate rate of 2.93 gpm.

The B-10 membrane must have a concentrate flow of 2.2 to 6.6 gpm to maintain the specified performance. (13) The membranes can be arranged in parallel, in series, or in a tapered configuration. In a parallel arrangement a larger pumping capacity is required, while in a series arrangement the downstream membranes are more vulnerable to fouling due to the highly concentrated feed. As a compromise, a tapered configuration staged 2:1:1 was selected and is shown in Figure 12. Feed and recycle waters are pumped to the two membranes in parallel within the first stage. Both concentrate streams of the first stage membranes are fed to a single membrane placed in the second stage. The concentrate of the second stage membrane is finally fed to the third stage. A portion of the third stage concentrate stream is bled to an incinerator and the rest of the stream is recycled back to the feed line. All permeate streams are collected into a product line. The numbers in the figure signify the flow rates of hospital wastewaters projected at various points. The product flow rate of 3.8 gpm is 30% greater than the required process rate of 2.93 gpm.

The overall performance of the RO membranes is improved in general as pressure and temperature increase. Therefore, it is advantageous to operate reasonably close to the maximum operating pressure and temperature specified for the membrane. The following operating conditions of the B-10 membrane are specified by the manufacturer: (13)

Operator Pressure, psia	815
Temperature Range, F	32 - 95
pH Range	5 - 9
Concentrate Flow Rate, gpm	2.2 - 6.6

Contaminant Removal Efficiencies of RO Membranes

The contaminant removal efficiencies of the B-10 RO membranes (7) for both the hospital composite wastewater and the natural brackish waters are as follows:

TABLE 9 PERMEATE FLOW RATES OF A B-10 PERMEATOR
AS A FUNCTION OF THE PRODUCT RECOVERY

<u>MUST Ultrafiltrate</u>	<u>Permeate Flow Rate (gpm)</u>	
	<u>80% Recovery</u>	<u>95% Recovery</u>
Hospital Composite	2.03	1.60
Shower	1.50	1.40
Operating Room	1.62	1.29
Kitchen	1.52	1.30
Laboratory	1.57	1.15
X-ray	1.55	1.07
Laundry Composite	1.80	1.60

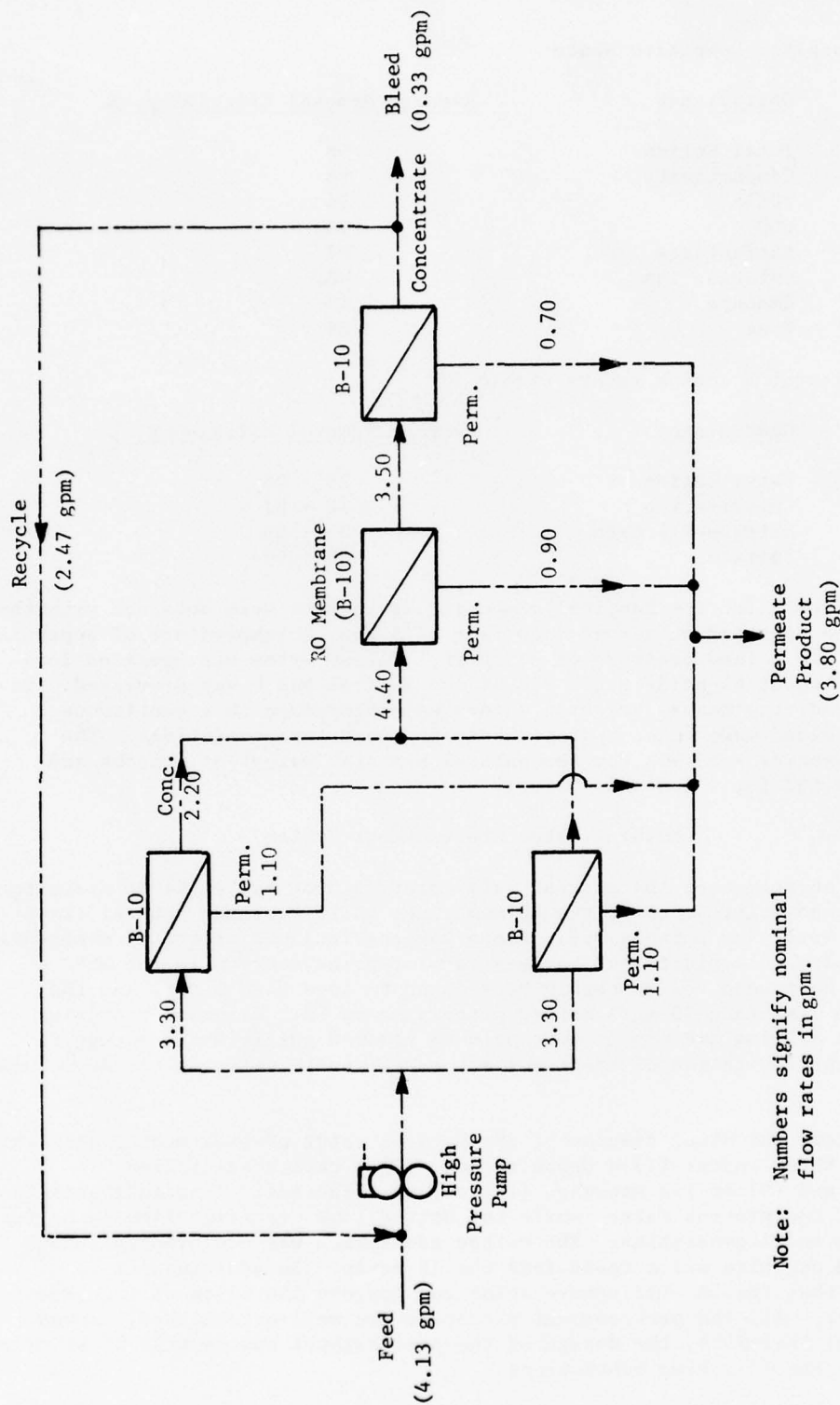


FIGURE 12 CONFIGURATION OF THE REVERSE OSMOSIS MEMBRANE ASSEMBLY

• Hospital Composite Waste

<u>Contaminant</u>	<u>Average Removal Efficiency, %</u>
Total Solids	98
Conductivity	98
TOC	76
COD	76
Surfactants	97
Chloride Ion	98
Ammonia	47
Urea	86

• Natural Brackish Waters (Table 7)

<u>Contaminant</u>	<u>Average Removal Efficiency, %</u>
Total Solids	73 - 98
Chloride Ion	70 - 97
Nitrate-Nitrogen	65 - 85
Sulfate	88 - 99+

The above results for the hospital composite wastewater were obtained with the B-10 membrane operated at a feed flow rate of 5 gpm, a temperature of approximately 85 F and a feed pressure of 815 psia. The RO sytem was operated in a batch mode without bleeding until 95% of the initial batch was processed. On the other hand, the natual brackish waters were processed in a continuous recycle-and-bleed mode under approximately the same test conditions. The product recoveries were 90% for the natural brackish waters of Arizona and Colorado and 50% for the Nevada water.

Natural Water Pretreatment System

The primary objective of the natural water pretreatment system is to minimize the fouling and maintenance of the RO membranes while treating natural fresh or brackish water for potable use. Among various foulants of the RO membranes, suspended solids, turbidity and hardness are of prime concern in the WPS operation. Suspended solids should be reduced to less than 5 mg/l and the turbidity to less than 10 mg/l before processing by RO. Hardness producing ions such as calcium and magnesium should be removed sufficiently enough to prevent the precipitation of their sulfate or carbonate salts on the RO membrane surface.

Figure 13 shows the block diagram of the natural water pretreatment system which consists of three units: (1) a depth filter, (2) a carbon adsorption (CA) column and (3) an ion exchange (IE) column. The solid line indicates the flow path of the process water, while the dotted line signifies flow paths for backflushing and regeneration. The carbon adsorption was employed to remove bacteria and organics which could foul the IE resin. In addition, it is anticipated that the CA will remove color and improve the taste of the processed potable water. All the pretreatment processes are well-established, proven technologies; therefore, the design of the pretreatment system will be briefly described in the following subsections.

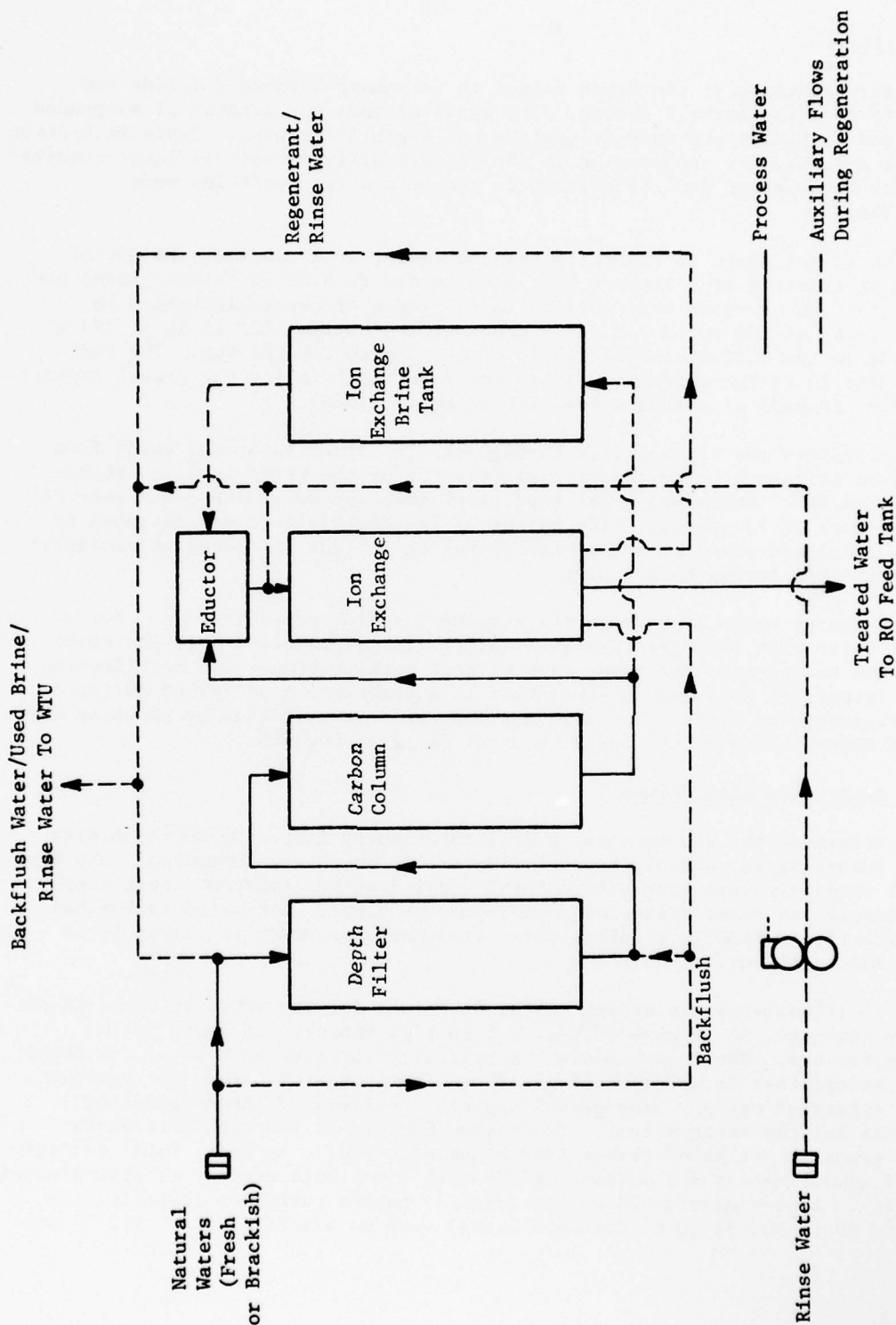


FIGURE 13 BLOCK DIAGRAM OF THE NATURAL WATER PRETREATMENT SYSTEM

Depth Filter

The primary function of the depth filter is to remove suspended solids and turbidity from the natural waters. The usual methods for removal of suspended solids and turbidity are sand filtration and depth filtration. Depth filtration (DF) was selected for application in the WPS primarily because of lower requirements for backwashing and the ability to remove smaller particles more effectively.

The depth filter shown in Figure 14 has a diameter of 12 in and a height of 54 in. It consists of a support bed, sand (0.016 to 0.02 in filter grade) and anthracite. The support bed contains three grades of quartz installed in three layers: (1) 26 lb of 1/2 x 1/4 grade at the bottom, (2) 13 lb of 1/4 x 1/8 grade in the middle, and (3) 13 lb of No. 4 grade on the top. The bed heights are 20 in for anthracite, 10 in for sand and 6 in for the gravel support. The column is made of carbon steel with an epoxy lining.

The water enters the depth filter through the top distributor and exits from the bottom collector. The superficial velocity of the water is 0.555 ft/min or 4.15 gpm/ft². Backwashing has been programmed for 20 minutes at a rate of 1.7 ft/min or 12.73 gpm/ft². The height of the depth filter was designed to allow a freeboard space at 60% of the filter bed height for adequate fluidization of the bed during backwashing.

The backwashing cycle depends on the suspended solids concentration. For natural water with 100 mg/l suspended solids, it is projected that the depth filter can be operated for seven days without backflushing. The backflushing in the Integrated Auto mode of operation is automatically performed during a DF/IE regeneration cycle. The regeneration cycle is initiated by pressing the IONEXCH REGEN button on the master control panel of the WPS.

Carbon Adsorption (CA) Column

The CA column in the WPU performs a dual function by filtering out turbidity and by adsorbing any dissolved organic materials which are introduced into the natural surface waters from both natural and industrial sources. Such organic contaminants can cause taste, odor and color problems. Activated carbon has been effectively used in drinking water treatments in order to eliminate or reduce such problems.

Figure 15 illustrates the design of the CA column for the WPU. It consists of a 12 in diameter, 54 in high column; a 6 in high support bed and a 30 in high carbon bed. The column design is basically the same as that of the depth filter except that an access port was installed in the CA column for removal of the exhausted carbon. The gravel support consisted of three grades of quartz as for the depth filter. The carbon bed was filled with Filtrasorb 200, a granular activated carbon from bituminous coal. It has a total surface area of approximately 4.3 million ft²/lb with a wet bulk density of approximately 30 lb/ft³. Approximately 90% of the granular carbon particles range in size from No. 40 to No. 12 (U.S. Standard Sieve) with an effective size of 0.02 in.

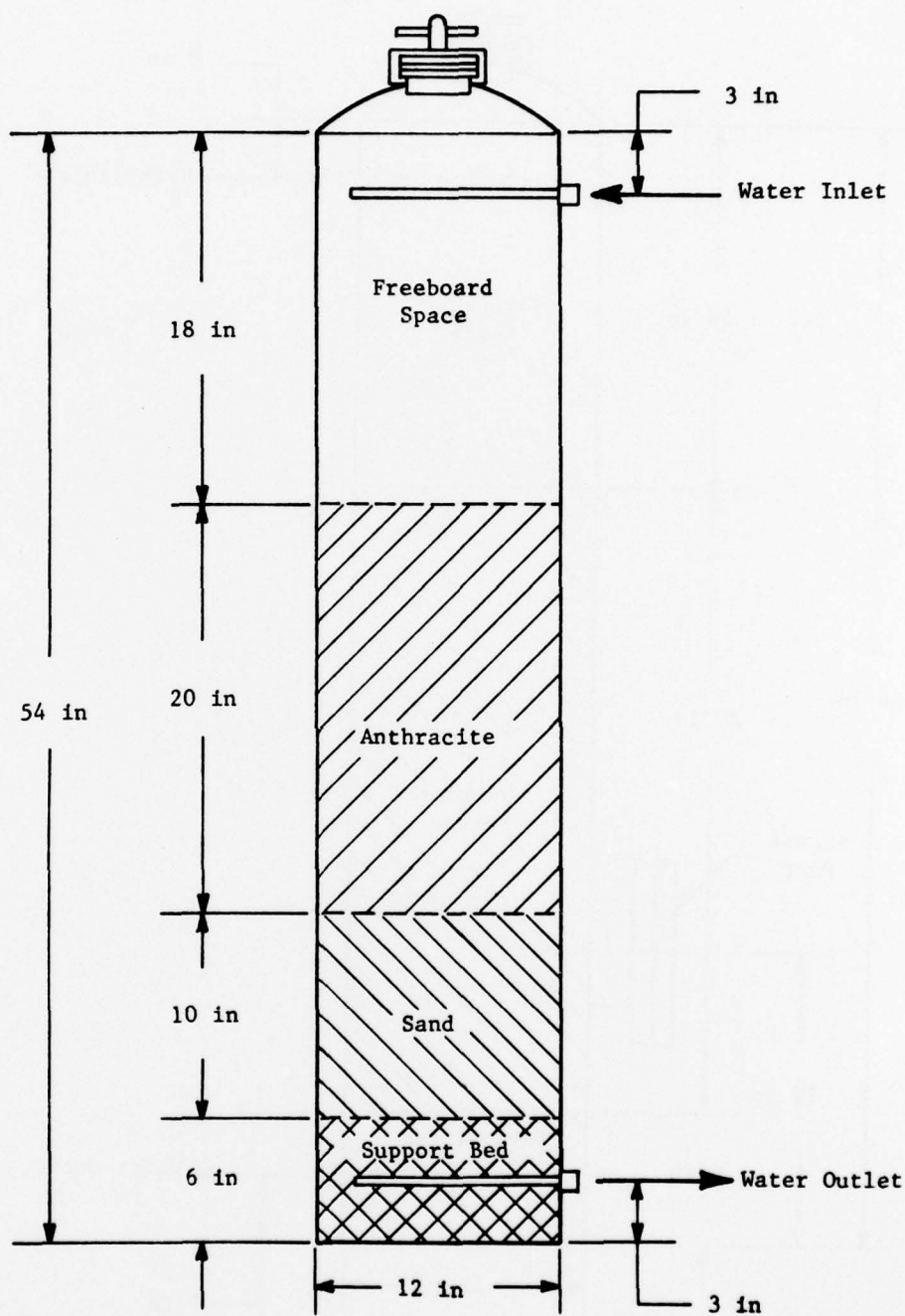


FIGURE 14 DEPTH FILTER

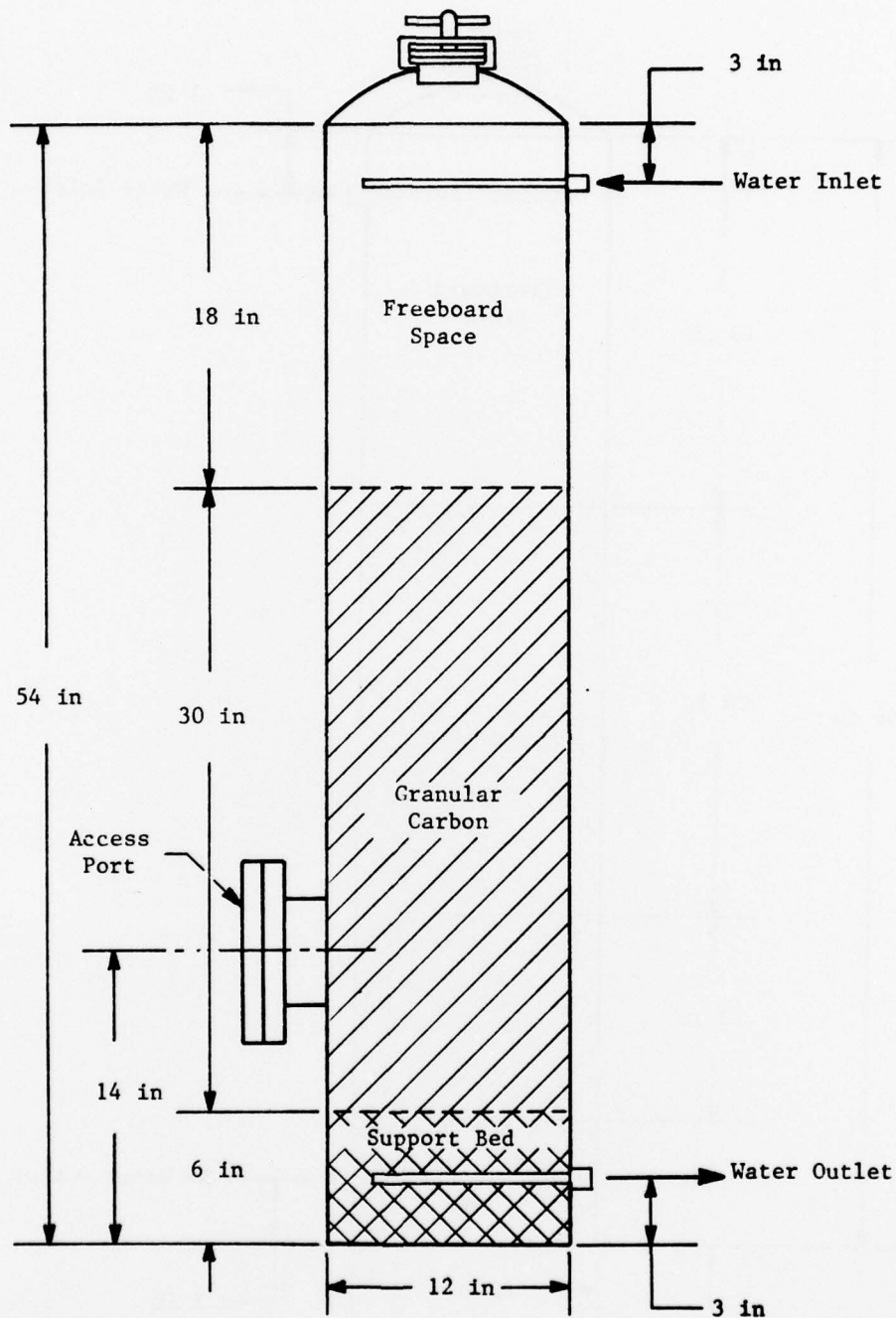


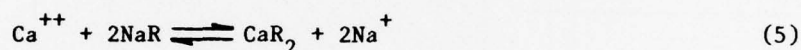
FIGURE 15 CARBON ADSORPTION COLUMN

The superficial velocity of water through the column was 0.555 ft/min or 4.15 gpm/ft². The pressure drop across the fresh carbon bed was estimated to be 8.5 in water under ambient temperatures. Backflushing of the carbon bed has to be done periodically in order to reduce the pressure drop buildup due to bed compaction. The backflushing was programmed for 15 minutes at a minimum rate of 1.02 ft/min or 7.64 gpm/ft². At this flush rate approximately 12% bed expansion was expected at a water temperature of 68 F. The 18 in high freeboard is high enough to accommodate up to 60% bed expansion when needed. Backflushing was automatically performed during the DF/IE regeneration cycle.

Ion Exchange (IE) Column

The primary function of the IE column was to remove multivalent metallic cations contributing to hardness. The metallic cations, such as calcium and magnesium which are present in natural surface waters, can cause fouling of the downstream RO membranes by precipitation of their sulfate or carbonate salts on the membrane surface.

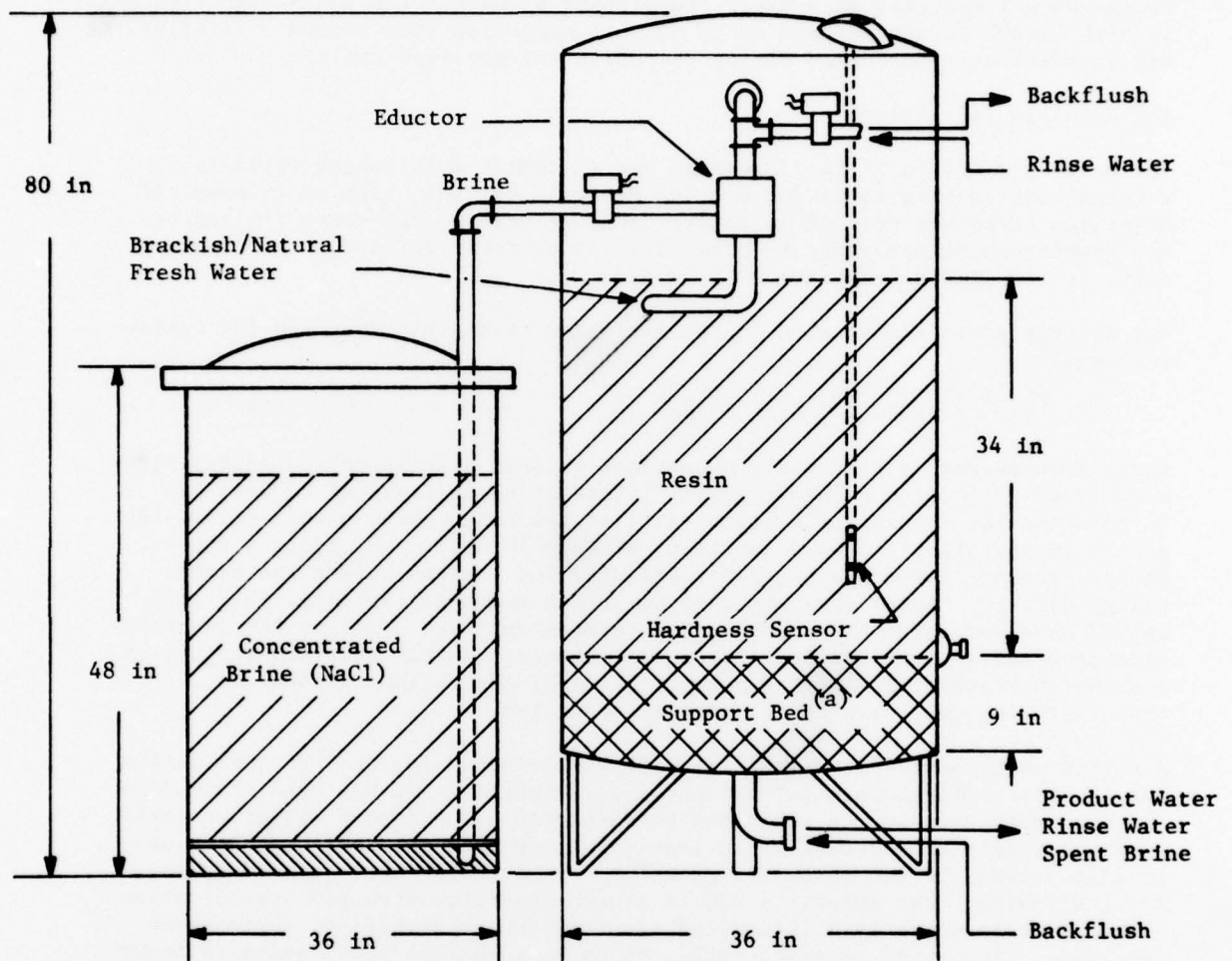
The IE process is illustrated in the following reversible reaction for cation exchange:



where R represents a stationary monovalent anionic site in the polyelectrolyte network of the cation exchange resin. Exchange of multivalent cations (Ca^{++}) in solution for monovalent cations (Na^+) in the resin phase occurs during the normal IE operation (forward reaction) because in dilute solutions a typical cation exchange resin has a greater affinity for cations having the higher charge density. After exhaustion of the resin exchange capacity, the resin should be regenerated according to the reverse reaction. During the regeneration step multivalent cations (Ca^{++}) are removed from the resin by the use of a solution containing a higher concentration of monovalent cations (Na^+), thus restoring the resin to its initial condition.

A cation exchange resin of Amberlite 200 was selected for the WPS application due to its excellent chemical and physical stability. It has been claimed by the manufacturer that the resin has consistently outperformed all other cation exchange resins in reducing resin loss resulting from physical breakdown and in eliminating the necessity for premature resin replacements caused by bead decrosslinking. The Amberlite 200 is a high-capacity, strongly acidic cation exchange resin which is a sulfonated, macroreticular styrene-divinylbenzene copolymer. The resin consists of No. 16 to 50 mesh size (U.S. Standard Sieve) spherical particles with a wet density of 50 lb/ft³ and an effective size of 0.016 to 0.020 in.

There are three major types of design in the IE operation: (1) batch, (2) semicontinuous, and (3) continuous. The semicontinuous design, the most frequently used method of fluid-solid contact, was employed due to the characteristic ON/OFF operation of the WPS. The semicontinuous design involves a fixed bed of the IE resin which can be regenerated during the four-hour maintenance period of the daily operation. The design of the IE unit is schematically shown in Figure 16. The IE unit consists of a 36 in diameter, 60 in



(a) Support Bed: 200 lb (0.37 x 0.63 in), 200 kg (0.19 x 0.37 in) and 248 lb (0.06 x 0.19 in) gravel.

FIGURE 16 ION EXCHANGE COLUMN

high resin column; a 36 in diameter, 48 in high brine tank and associated components such as valves and plumbing. The IE resin column contains a 34 in high resin bed, a 9 in gravel support bed and a 17 in high freeboard space for a maximum 50% expansion of the resin bed during backwashing. The 210 gal brine tank contains salt (NaCl) and a minimum 100 gal of a concentrated (approximately 26% NaCl) brine solution.

The required resin volume was sized for almost complete (greater than or equal to 99%) removal of hardness (1000 mg/l as calcium carbonate (CaCO_3)) in the natural surface waters at a process rate of 3.26 gpm and for 20 hours of continuous operation without regeneration.

Provided that the resin bed would have to be regenerated at the 70% exhaustion of its initial ion exchange capacity, a resin volume of 20.5 ft³ including a 40% excess capacity was specified. The resin selected has a hardness removal capacity of 22,200 grains of CaCO_3 /ft³ resin at a regeneration level of 10 lb NaCl/ft³ resin.⁽¹⁴⁾ For an efficient utilization of the resin exchange capacity, the highest column is desired in an allowable range of the pressure drop across the resin bed. In the WPS, the maximum height of the IE column was dictated by the physical dimensions of a ward container in which the WPU is to be packaged. The superficial velocity of the process water through the resin bed is 0.062 ft/min or 0.46 gpm/ft². The pressure drop across the resin bed is estimated to be 3 in water at 68 F.

The regeneration of the IE resin bed consists of three steps: (1) backflushing the column with natural waters to loosen and reclassify the resin particles, (2) regenerating the resin by passing a 10% NaCl solution through the resin bed so that the resin may be converted from the exhausted condition to the initial condition of the ionic form, and (3) rinsing the regenerated resin bed with potable water to flush out the regenerant NaCl solution remaining in the bed and to prevent air from being trapped in the bed. The backwashing was programmed for 10 minutes at a superficial velocity greater than 0.57 ft/min or 4.23 gpm/ft² to give a minimum 35% bed expansion. During the regeneration step a concentrated (approximately 26%) NaCl solution from the brine tank was induced into the eductor by a flow of the natural waters pretreated in the depth filter and CA units. The flow rate of the NaCl solution is set at 2.5 gpm to produce approximately 10% NaCl regenerant when mixed with 4 gpm of the natural waters. Following 30 minute regeneration the resin bed was rinsed with potable water for 20 minutes at a rate of 8.3 gpm. The IE regeneration in the Integrated Auto mode of operation is automatically performed when initiated by the operator by pressing the IONEXCH REGEN button on the master control panel of the WPS. The operator is continuously informed of the exhaustion status of the IE resin bed by three hardness sensors located in the bed.

Hypochlorination Unit

The HC unit is designed to provide a free-available chlorine residual of 5 mg/l in the potable and the reuse water for disinfection (see Figure 4). In the Potable Mode, the RO permeate of the natural water stream leads directly to the HC unit, while in the Reuse Mode the RO permeate of the hospital wastewater is further treated in the O₃/UV Unit before hypochlorination. A single HC unit is used for hypochlorination of both streams.

The HC unit consists of a hypochlorite storage tank, a hypochlorite feed pump and static mixers. The storage tank, constructed of polyethylene, contains 50 gal of hypochlorite solution. The pump has variable speeds to permit control of the hypochlorite dose rate. Three 0.75 in diameter suspended solids static mixers were installed in series to mix the product waters with the hypochlorite solution.

In order to maintain a constant level of free-available chlorine residual, the hypochlorite dose rate should be determined by the chlorine demand and the flow rate of the product water. The chlorine demand of the product water varies depending on the water source. The chlorine dosage control on the WPU front panel has six ranges in the hypochlorite feed flow rate which are manually adjusted according to the water source. Once the chlorine dosage control is set the hypochlorite dose rate is automatically controlled in a feed-forward mode by the output of a flow sensor located upstream of the HC unit.

Control/Monitor Instrumentation

Both automatic and semiautomatic instrumentations were incorporated into the WPU design to control and monitor the system performance. Only the semiautomatic instrumentation will be described in this section. Detailed descriptions of the automatic instrumentation can be found elsewhere.^(2,5) The objective of the semiautomatic instrumentation was to provide a pilot testing capability for evaluation of the WPU performance.

Control Features

The following major control features were incorporated in the WPU:

1. Automatic fail-safe shutdown initiated by seven alarm conditions (Table 3)
2. Automatic temperature control
3. Automatic pH control
4. Automatic control of the water level in the RO feed tank
5. Automatic selection of a set of clean filters when the other set is filled with filtered solids
6. Feed water pressure to the RO membranes manually controlled by a backpressure regulator
7. Six ranges of the hypochlorite feed rate can be manually selected by a chlorine dosage switch on the front panel
8. The chlorine dose rate is automatically controlled in a feed-forward mode according to the water flow rate
9. A total of 29 control switches for pumps and valves are incorporated on the front instrumentation panel

Monitor Features

The following monitor features were incorporated in the WPU:

1. Water temperature and pH in the RO system
2. Conductivity of the RO permeate
3. Pressures of the RO feed and the DF feed water
4. Pressure drops across the filters, membranes and depth filter
5. Flow rates of the recycle and the permeate stream in the RO system
6. Accumulated total flow of the RO permeate
7. A total of ten light indicators provide warning and alarm conditions

CONCLUSIONS

The following conclusions were drawn from this development program:

1. The concept of the integrated, transportable WPS is a viable solution to meet the needs for the multipurpose water treatments in field Army medical facilities.
2. The WPU is capable of purifying typical natural waters for potable use. It can be the principal treatment unit for the production of nonpotable reuse water from the field hospital wastewaters. The reverse osmosis separation is the key process of the WPU.
3. The prototype WPU can be easily housed in a standard ward container having inside dimensions of 11.5 x 6.5 x 6.75 ft for transportation via conventional routes. They include standard cargo trucks, external helicopter loads, railroad, ship or cargo aircraft.
4. The semiautomatic instrumentation and a number of flexibilities enable the WPU to serve as a test bed for the purpose of general water treatment process evaluations.

RECOMMENDATIONS

The following recommendations are direct results of this study:

1. Integrated testing of the WPS with simulated hospital wastewaters should be performed to evaluate and characterize the performances of the WPU and the WPS.
2. In addition to the hospital wastewater treatment, the WPU should be used as a flexible test bed to evaluate the treatability of various kinds of wastewaters generated in other Army installations.

3. Extensive field testing of the WPU is recommended to evaluate the WPU performances for purifying natural waters in various geographic locations. Certain natural waters are known to contain traces of carcinogens such as trihalomethanes. To eliminate such contaminants, the UV/ozone oxidation process may have to be included in the WPU.
4. The semiautomatic instrumentation and other flexibilities of the WPS pilot plant should be eliminated in the prototype system.

REFERENCES

1. "Medical Unit, Self-Contained Transportable (MUST) Manual for MUST Equipped Medical Units," Academy of Health Science, U. S. Army, Ft. Sam Houston, TX, March, 1974.
2. Lee, M. K., Yang P. Y., Wynveen, R. A. and See, G. G., "Pilot Plant Development of an Automated, Transportable Water Processing System for Field Army Medical Facilities," Final Report, Contract DAMD17-76-C-6063, ER-314-7-1, Life Systems, Inc., Cleveland, OH, June, 1978.
3. Lee, M. K., Yang, P. Y. and Wynveen, R. A., "Water Treatment Unit Development for Field Army Medical Facilities," Technical Report, Contract DAMD17-76-C-6063, ER-314-7-2, Life Systems, Inc., Cleveland, OH, March 1978.
4. Lee, M. K. and Yang, P. Y., "UV/Ozone oxidation Technology Development for Water Treatment for Field Army Medical Facilities," Technical Report, Contract DAMD17-76-C-6063, ER-314-7-5, Life Systems, Inc., Cleveland, OH, July, 1978.
5. Yang, P. Y., Yeh, J. Y., Powell, J. D. and Wynveen, R. A., "Advanced Instrumentation Development for a Water Processing Pilot Plant for Field Army Medical Facilities," Technical Report, Contract DAMD17-76-C-6063, ER-314-7-4, Life Systems, Inc., Cleveland, OH, May, 1978.
6. Lambert, W. P. and McCarthy, J. J., "Ozone Oxidation for Reuse of Army Field Hospital Wastewaters," IOI Forum on Ozone Disinfection, Ozone Press Int., 108, (1977).
7. Gollan, A. Z., McNulty, K. J., Goldsmith, R. L. Kleper, M. H. and Grant, D. C., "Evaluation of Membrane Separation Processes, Carbon Adsorption, and Ozonation for Treatment of MUST Hospital Wastes," Final Report, Contract DAMD17-74-C-4066, ADAO 30057, Walden Research Division of Abcor, Inc., Wilmington, MA, August, 1976.
8. McCarthy, J. J., "Ozonation of Synthetic Hospital Composite RO and UF Permeate Using the Westgate Unit Reactor Module," Memorandum to W. P. Lambert, May 17, 1977.
9. See, G. G. and Yang, P. Y., "Water Processing Element Operation Manual," Contract DAMD17-76-c-6063, ER-314-38, Life Systems, Inc., Cleveland, OH, September, 1977.

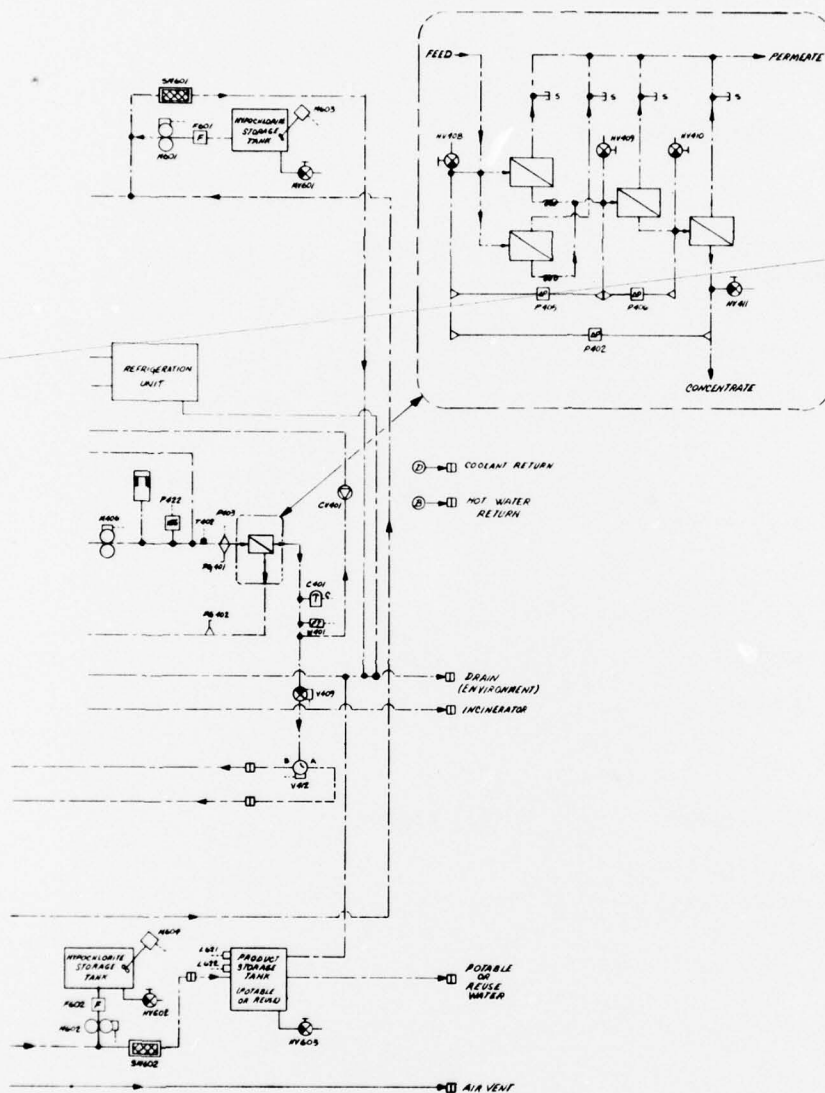
10. McCarthy, J. J., "MUST Composite Wastewater UF and RO Permeates," Memorandum to W. P. Lambert, March 31, 1977.
11. U. S. Army Medical Research and Development Command RFQ No. DAMD17-76-Q-6561, "MUST Water Processing Element Pilot Plant Development," May 3, 1976.
12. See, G. G., Yang, P. Y. and Kacholia, K. K., "Research and Development of an Ozone Contactor System," Final Report, Contract DAMD17-76-C-6041, ER-300-4, Life Systems, Inc., Cleveland, OH, June, 1976.
13. Dupont Company Technical Bulletin No. 260, "Permasep Permeator Product Specifications," March 1, 1976.
14. Rohm and Haas Technical Bulletin No. IE-127-67, "Amberlite 200," November, 1974.

APPENDIX 1

FLOW SCHEMATIC OF WATER
PROCESSING ELEMENT PILOT PLANT

OUTPUTS

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CONTROL AND
MONITOR
INSTRUMENTATION
+ SEMI-AUTOMATIC
+ AUTOMATIC

PORTABLE
PUMP

NOTE: 1) SAMPLE VALVES SHOWN AT THE TOP AND BOTTOM OF
SYMBOL 1 OF THE OZONE CONTACTOR ARE ON ALL STAGES
BUT NOT SHOWN FOR SIMPLICITY.

SYSTEM SYMBOLS

- ① NOT AIR
- ② NOT AIR RETURN
- ③ COOLANT
- ④ COOLANT RETURN
- ⊗ ELECTRICAL SHUTOFF VALVE, NORMALLY OPEN
- ⊙ PRESSURE REGULATOR
- ⊕ VARIABLE ORIFICE (MANUAL)
- ⊖ VARIABLE ORIFICE (ELECTRICAL)
- ⊗ ELECTRICAL SHUTOFF VALVE, NORMALLY CLOSED
- ⊙ FLOW RATE / TOTALIZER
- ⊕ MANUAL SHUTOFF VALVE
- ⊖ RELIEF VALVE
- ⊗ ELECTRICAL THREE WAY VALVE
- ⊙ TEMPERATURE READOUT (MAX-MIN-MAX)
- ⊕ PUMP
- ⊖ CHECK VALVE
- ⊗ SAMPLING PORT CAPTEE
- ⊙ PRESSURE SENSOR (GAUGE TYPE)
- ⊕ PRESSURE SENSOR (ELECTRICAL TYPE)
- ⊖ CONNECTOR
- ⊗ LEVEL SENSOR
- ⊙ CONDUCTIVITY MONITOR/CONTROLLER
- ⊕ TEMPERATURE SENSOR
- ⊖ TRAP
- ⊗ TURBIDITY MONITOR/CONTROLLER
- ⊙ DIFFERENTIAL PRESSURE TRANSDUCER
- ⊕ PH MONITOR/CONTROLLER
- ⊖ HEAT EXCHANGER
- ⊗ ACCUMULATOR
- ⊙ FLOWMETER WITH FLOW CONTROL
- ⊕ FOUR WAY VALVE (MANUAL)
- ⊖ COMPRESSOR
- ⊗ FILTER
- ⊙ LOW PRESSURE SWITCH
- ⊕ PH SENSOR
- ⊖ FLOW RATE MONITOR
- ⊗ FREE CHLORINE SENSOR
- ⊙ HIGH PRESSURE SWITCH
- ⊕ TOC MONITOR/CONTROLLER
- ⊖ POWER SOURCE
- ⊗ DEW POINT SENSOR
- ⊙ FLOW SWITCH
- ⊕ FORM TRAP
- ⊖ ORIFICE
- ⊗ MANUAL THREE-WAY VALVE
- ⊙ LIQUID LINE
- ⊕ ELECTRICAL LINE
- ⊖ GAS LINE
- ⊗ OZONE IN AIR MONITOR
- ⊙ HARDNESS MONITOR
- ⊕ ULTRA VIOLET LIGHT
- ⊖ DISSOLVED OZONE IN WATER MONITOR
- ⊗ EDUCTOR
- ⊙ MIXER
- ⊕ TEMPERATURE SWITCH
- ⊖ STATIC MIXER
- ⊗ FLOW RESISTOR
- ⊙ HUMIDITY SWITCH

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